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Component Fragility Research Program

Phase I Component Prioritization

G. S. Holman, C. K. Chou

Prepared for
U.S. Nuclear Regulatory Commission

Lawrence
Livermore
National
Laboratory

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Component Fragility Research Program

Phase I Component Prioritization

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ABSTRACT

Current probabilistic risk assessment (PRA) methods for nuclear power plants utilize seismic "fragilities -- probabilities of failure conditioned on the severity of seismic input motion -- that are based largely on limited test data and on engineering judgement. Under the NRC Component Fragility Research Program (CFRP), the Lawrence Livermore National Laboratory (LLNL) has developed and demonstrated procedures for using test data to derive probabilistic fragility descriptions for mechanical and electrical components. As part of its CFRP activities, LLNL systematically identified and categorized components influencing plant safety in order to identify "candidate" components for future NRC testing. Plant systems relevant to safety were first identified; within each system components were then ranked according to their importance to overall system function and their anticipated seismic capacity. Highest priority for future testing was assigned to those "very important" components having "low" seismic capacity. This report describes the LLNL prioritization effort, which also included application of "high-level" qualification data as an alternate means of developing probabilistic fragility descriptions for PRA applications.

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IV

CONTENTS

page

ABSTRACT.. iii
FIGURES... vii
TABLES.. ix
ACKNOWLEDGEMENTS.. xi

1. INTRODUCTION

1.1 Background.. 1-1
1.2 The Charleston Issue...................................... 1-3
1.3 Phase I Objectives.. 1-5
1.4 Definition of Component Fragility......................... 1-6
1.5 Phase I Demonstration Tests............................... 1-12

2. COMPONENT PRIORITIZATION

2.1 General Approach.. 2-1 -18
2.2 General Assumptions....................................... 2-5 -22
2.3 General Conditions and Plant States....................... 2-7 -24
2.4 Development of Prioritization............................. 2-8 -25
2.5 Comparison Against Data................................... 2-14 -31
2.6 Implications for Fragility Evaluation..................... 2-18 -35

3. FRAGILITY DEVELOPMENT FROM "HIGH-LEVEL" QUALIFICATION DATA

3.1 General Discussion.. 3-1 -57
3.2 4160-Volt Metal-Clad Switchgear........................... 3-3 -59
3.3 Safeguard Relay Boards.................................... 3-14 -70
3.4 Potential Transformer..................................... 3-20 -76
3.5 Emergency Light Battery Pack.............................. 3-23 -79
3.6 Station Battery and Racks................................. 3-26 -82
3.7 Discussion of Results..................................... 3-28 -84

4. SUMMARY AND CONCLUSIONS

4.1 Component Prioritization.................................. 4-1 -116
4.2 Development of Fragilities from Existing Data............. 4-3 -118
4.3 Conclusions... 4-4 -119

BEST COPY AVAILABLE

CONTENTS (cont.)

5. RECOMMENDATIONS FOR PHASE II

5.1 General Approach to Fragilities Testing.................... 5-1-121
5.2 Recommendations for Phase II Testing....................... 5-3-123
    5.2.1 Medium-Voltage (4kV) Switchgear...................... 5-3
    5.2.2 Emergency Safety Function Sequence................... 5-4-124
    5.2.3 Safety Relay Board................................... 5-4
    5.2.4 Local Starters....................................... 5-5-125
    5.2.5 Electrical Distribution Equipment.................... 5-5
    5.2.6 Battery Chargers..................................... 5-5
5.3 Testing Alternatives....................................... 5-6-126

REFERENCES 6-1-130

APPENDICES

Appendix A: Component Ranking Matrix

Appendix B: Master List of Safety-Related Equipment,
Millstone Unit 3

Appendix C: Comparison of Subjective Seismic Capacity Levels with
Levels Inferred by Qualification Data

FIGURES

page

1-1. Typical curve set representing component fragility 1-15

1-2. Typical 95% fragility function showing how increasing random uncertainty affects median capacity derived from a HCLPF value 1-16

1-3. Typical 95% fragility function showing how increasing random uncertainty affects the HCLPF value derived from a constant median capacity 1-17

2-1. General approach for component prioritization 2-22

2-2. Flow diagram of Zion residual heat removal system 2-23

3-1. 4160-volt switchgear on test stand prior to removal of potential transformers 3-35

3-2. 4160-volt switchgear on test stand after removal of potential transformers 3-36

3-3. Typical overcurrent relay 3-37

3-4. Induction unit for typical overcurrent relay 3-38

3-5. Locations of accelerometers for monitoring switchgear response motions 3-40

3-6. Input motion TRS and response spectrum at switchgear Location 7 during Run 16, S-S direction (5% damping) 3-41

3-7. Input motion TRS and response spectrum at switchgear Location 7 during Run 16, vertical direction (5% damping) 3-42

3-8. Input motion TRS and response spectrum at switchgear Location 7 during Run 31, F-B direction (5% damping) 3-43

3-9. Input motion TRS and response spectrum at switchgear Location 7 during Run 31, vertical direction (5% damping) 3-44

3-10. Envelope of horizontal input motion TRS (3% damping) 3-45

3-11. Minimum horizontal seismic capability of the switchgear, expressed as response spectra at indicated damping values 3-46

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3-12. Front view of safeguard relay board, with the 4.16 kV switchgear potential transformer mounted alongside 3-47

3-13. Side view of the safeguard relay board, with the emergency light pack mounted separately in front 3-48

3-14. Locations of (a) accelerometers on safeguard relay board front panel and (b) strain gauges near cabinet base 3-49

3-15. Input motion TRS and response spectrum at relay board Location 1 during Run 14, F-B direction (3% damping) 3-50

3-16. Input motion TRS and response spectrum at relay board Location 1 during Run 14, vertical direction (3% damping) 3-51

3-17. Input motion TRS and response spectrum at relay board Location 1 during Run 27, S-S direction (3% damping) 3-52

3-18. Input motion TRS and response spectrum at relay board Location 1 during Run 14, F-B direction (3% damping) 3-53

3-19. Envelope of input motion TRS for safeguard relay board, both horizontal directions (3% damping) 3-54

3-20. Minimum horizontal seismic capability of the safeguard relay board, expressed as a 3% damping response spectrum 3-55

3-21. Test configuration for two battery cells and racks. Note braced modifications 3-56

3-22. Fragility curves for 4 kV switchgear estimated from results of qualification testing 3-57

3-23. Estimated fragility curves for potential transformer, safeguard relay board, and emergency light battery pack 3-58

3-24. Estimated fragility curves for station battery and racks 3-59

TABLES

page

2-1. Systems or functions required to maintain plant safety 2-24

2-2. Systems identified according to plant safety function 2-25

2-3. Components reviewed for reactivity control 2-27

2-4. Components reviewed for reactor coolant inventory control 2-28

2-5. Components reviewed for maintaining reactor coolant pressure boundary integrity 2-29

2-6. Components reviewed for providing core cooling 2-29

2-7. Components reviewed for decay heat removal 2-31

2-8. Components reviewed for maintaining plant environment 2-32

2-9. Components reviewed for maintaining containment integrity 2-33

2-10. Components reviewed for maintaining onsite electrical power 2-34

2-11. Components reviewed for providing instrumentation and control 2-35

2-12. Components reviewed for maintaining vital auxiliaries 2-36

2-13. Summary of components ranked as "low-capacity" (Capacity Group 3) 2-37

2-14. Summary of components ranked as "intermediate-capacity" (Capacity Group 2) 2-38

2-15. Summary of components ranked as "high-capacity" (Capacity Group 1) 2-39

3-1. Safeguard relay board "H" device table 3-32

3-2. Seismic fragility expressed in terms of local base ZPA 3-34

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1. INTRODUCTION

1.1 Background

Over the past decade methods have been developed to assess probabilistically how large earthquakes would affect nuclear power plants, particularly the associated risk to public health and safety. These probabilistic risk assessment (PRA) techniques combine "event trees", which describe the postulated accident scenarios (or "initiating events") capable of causing core melt, with "fault trees" describing the likelihood of equipment failures leading to a reduction in or loss of the ability of certain plant systems to perform their designated safety functions given that an initiating event occurs. A key element in the fault tree analysis is the "fragility" -- or likelihood of failure -- of various components under postulated accident conditions.

Application of these analysis techniques, both in NRC-sponsored research such as the Seismic Safety Margins Research Program and in commercial PRA studies, has indicated that potential accidents initiated by large earthquakes are one of the major contributors to public risk. However, component fragilities used in these analyses are for the most part based on limited data -- primarily design information and results of component "qualification" tests -- and engineering judgement. The seismic design of components, in turn, is based on code limits and NRC requirements that do not reflect the actual capacity of a component to resist failure; therefore, the real "seismic margin" between design conditions and conditions actually causing failure may be quite large. These elements combine to produce fragilities that are not only highly uncertain but also, in the view of many experts, are overly pessimistic descriptions of the likelihood of failure for many components. The observed performance of mechanical and electrical equipment in non-nuclear industrial facilities that have experienced strong-motion earthquakes tends to support this view. However, this same experience has also indicated that although a component may itself perform well in an earthquake, poor or inadequate support conditions may increase the likelihood of its "failure" in a safety sense. This also holds true in certain cases for aging or

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environmental effects, which may require attention if an "adequate" description of fragility is to be achieved.

In order to improve the present fragility data base and develop realistic input for probabilistic risk assessments and seismic margin studies, the NRC commissioned a Component Fragility Research Program (CFRP). The CFRP is being conducted in two phases. Phase I comprised parallel efforts to (1) develop and demonstrate procedures for testing components to obtain new fragilities data, (2) identify by systematic ranking those components that most influence plant safety and are therefore candidates for NRC testing, and (3) compile and evaluate existing fragilities data obtained from various sources. The results of these three activities form the basis for a comprehensive evaluation of component behavior, based both on available data and on new testing, to be performed in Phase II of the program.

The CFRP supports the need for realistic inputs for probabilistic risk assessments and margin studies. This research seeks to test the hypothesis that electrical and mechanical components have greater seismic capacity that is presently assumed in seismic risk assessments, and, as a consequence, that the significance of the earthquake threat might be diminished in licensing decision making. In particular, the CFRP will result in the following:

- more realistic inputs for PRA applications. Improved descriptions of component fragility, based on actual failure data, will reduce the uncertainty inherent in subjective fragilities drawn from design information and results of equipment qualification testing.

- better understanding of component failure modes, of how various individual factors affect failure, and of the real "margin" between design or qualification requirements and conditions that might actually cause failure.

- guidance for development of seismic review procedures for existing plants, for interpretation of existing qualification or fragility data, and for specification of test procedures of equipment for which in-depth testing to "failure" is warranted.

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These results will combine to improve our ability to more realistically assess seismic risk while at the same time contributing to elimination of unnecessary licensing delays to respond to seismic issues.

1.2 The Charleston Issue

One immediate issue facing the NRC in particular and the nuclear industry as a whole is that of potential revisions in the seismic design bases for older plants. Most older plants located in the eastern U.S. were either not subjected to the in-depth seismic design typical of more modern plants, or were designed for relatively low levels of safe shutdown earthquake (SSE). This practice reflected the long-held view that the eastern United States (i.e., east of the Rocky Mountains) was historically an area of generally low seismicity with only a few isolated records of large earthquakes. However, recent studies have suggested that the seismology of the region is such that the effects of large earthquakes -- such as those near Charleston, South Carolina in 1889 and New Madrid, Missouri in 1811-12 -- could affect much wider geographic areas than originally believed. The results of these studies therefore present NRC with the problem of resolving what constitute "more appropriate" design basis earthquakes for plants in this region.

Resolution of the "Charleston issue" brings with it the prospect of SSE levels significantly higher than the original design bases for plants. Reevaluation of certain plants for these higher SSE levels could result in certain design allowables being exceeded, potentially jeopardizing the continued operation of these plants. However, exceedance of design allowables does not necessarily compromise plant safety, if it can be shown that sufficient "reserve" capacity is available to absorb increases in postulated seismic loads. At least three potential options exist for this purpose:

- Demonstrate equipment "ruggedness." Mechanical and electrical equipment related to plant safety is typically "qualified" to demonstrate its ability to function as intended during a site-specific SSE. The "seismic margin" between design level and actual failure is not typically measured

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as a part of qualification testing; most experts believe, however, that many equipment items have sufficiently high seismic capacity -- or "inherent ruggedness" -- that they would continue to function normally even when subjected to input motions well in excess of qualification requirements.

Demonstrating that this ruggedness exists, either through actual failure tests or by alternate means, therefore represents one potential response to a revision in SSE levels. Many organizations are actively pursuing this option. The Electric Power Research Institute (EPRI), for example, is currently applying existing qualification data to develop "Generic Equipment Ruggedness Spectra" (or "GERS") for certain items of plant equipment. Together with EPRI, the Seismic Qualification Utility Group (SQUG), comprising plant owners potentially affected by the Charleston issue, is compiling information on the performance of heavy industrial facilities (which contain many equipment items typically found in nuclear power plants) during actual strong earthquakes.

- Perform "less conservative" response analyses. Equipment in many older plants may have high seismic margins owing to relatively conservative response analyses being used in plant design (e.g., to predict equipment input motions). Many factors can affect the degree of conservatism, including (1) the specific analytic methods used to predict component response (e.g., two- vs three-dimensional finite-element analysis, time-history vs response spectrum analysis, coupled vs uncoupled analysis), either singly or in combination, (2) input data such as damping values, and (3) application of safety factors to calculated results to "insure" conservatism. Just what constitutes a "conservative" analysis is subject to interpretation, but in general the less sophisticated an analysis is, the more conservative it tends to be.

If design is done by analysis, the apparent margin is influenced by the particular analytic method used. A "conservative" method of analysis may

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result in an artificially low margin. Taking advantage of more refined -- "less conservative" -- analysis techniques to evaluate an older plant thus represents a possible means of more realistically predicting (i.e., reducing) responses to increased seismic loads in order to meet revised design criteria.

- Apply revised NRC requirements. Recent or pending changes in NRC regulations affecting postulated design loads allow or would allow relaxations such as decoupling SSE and certain loss-of-coolant accident (LOCA) loads, elimination of dynamic effects (pipe whip, jet impingement, hydrodynamic loads) associated with certain pipe breaks, and use of alternative descriptions of damping. Plants originally designed for loads or load combinations affected by the regulatory actions might benefit in that these loads or load combinations would no longer need to be considered in a reevaluation for increased seismic loads, or would be reduced through use of alternative (i.e., more realistic) input criteria for calculating loads.

The investigation discussed in this report concerns itself with the first of these items, namely equipment ruggedness. It is important to keep in mind, however, that future responses to more stringent seismic design criteria may be able to take credit of all three to one extent or another. Consequently, any assessment of seismic capacity must take the other two factors into account in order to assure it is conducted on a reasonable basis.

1.3 Phase I Objectives

During Phase I of the CFRP, the Lawrence Livermore National Laboratory (LLNL) has performed component testing and prioritization, while the existing fragilities data base has been compiled by the Brookhaven National Laboratory (BNL). The specific objectives of the Phase I LLNL effort have been as follows:

Component Prioritization

- systematically identify and categorize electrical and mechanical components influencing plant safety, taking into account system and subsystem functional descriptions, operating and maintenance experience, expert opinion, past PRA results, regulatory concerns and existing test data.
- collect and utilize existing test data and operating experience to assess the relative seismic capacity of each component identified.
- identify "very important, low seismic capacity" components which then become priority candidates for future comprehensive testing.

Demonstration Testing

- develop procedures for component fragilities and seismic margins testing and demonstrate the effectiveness of these procedures through actual component tests.
- obtain useful fragilities and seismic margins data for the components tested.
- enhance understanding of failure mechanisms of the components tested.

This report describes our Phase I component prioritization activities. The Phase I demonstration testing program is documented in a companion report [1].

1.4 Definition of Component Fragility

"Fragility" is a term commonly used to describe the conditions under which a component (or, in general, a structure, a piping system, or piece of equipment) would be expected to fail. In this report we are concerned with *seismic* fragility, in other words, what levels of earthquake-induced input motion would be required to cause component failure; it is important to keep in mind, however, that fragility can in principle be defined for *any* input condition affecting component performance. Failure can be characterized as either functional (e.g., erratic behavior, failure to perform intended function) or physical, or as the exceedance of some predetermined performance criteria (such as a limit given in a design code).*

One interpretation of component fragility -- which we will refer to as the "fragility level" -- evolves from qualification testing. In seismic qualification testing, a component is subjected to input motion characterized by a specified waveform describing input level (seismic acceleration) as a function of frequency. The component is "qualified" if it continues to perform its intended function when its response to this input motion -- the "test response spectrum," or TRS -- meets or exceeds pre-determined acceptance limits (the "required response spectrum," or RRS). In qualification testing, the TRS is usually measured at the component support points.

Although it may establish the adequacy of a component for a particular seismic environment, a successful qualification test does not directly provide data on what input motion levels actually result in component failure. This can be (and sometimes is) done by retaining the original input spectrum and then increasing the input *level* until "failure" (however it is defined) occurs. The TRS at failure represents the "fragility level" or "ruggedness" of the component; the difference between the fragility level and the qualification level thus represents the seismic margin of the component.

Fragility is described differently when used for PRA purposes or for other types of probabilistic analysis. In this case, the fragility of a component represents the probability of its failure -- or more rigorously speaking, the probability of attaining a defined "limit state" -- conditioned upon the occurrence of some level of forcing or response function. It may be expressed in terms of a local response parameter (for example, input motion at the component mounting location) or can be tied to a more global forcing function such as free field peak ground acceleration (PGA). Note however that when fragility is anchored to a forcing function, the further removed the component is from that forcing function, the more factors there are (such as structural response and soil-structure interaction) that must be considered in the fragility description.

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* In this discussion "physical failure" is used instead of the more common term "structural failure" to make clear that we are concerned only with mechanical and electrical equipment, and not with plant structures.

The probability of failure is typically described by a family of "fragility curves" plotted at various levels of statistical confidence (see Fig. 1-1). The central, or "median" function represents the fragility analyst's best estimate of the "true" fragility of the component taking into account all significant factors which, in the analyst's judgement, might contribute to failure. The central point (50% probability of failure) on this curve represents the "median capacity" of the component; ideally, this probabilistic value would correspond with the deterministic "fragility level" of the component. The fragility function is a cumulative distribution usually characterized by a log-normal function with this median value and a logarithmic standard deviation β_R which describes the "random" variation in the parameters affecting fragility. In a description of seismic fragility, for example, this parameter might represent the differences in real earthquake ground motion compared to the input motion that a component is subjected to in qualification or fragilities testing. Note that the random uncertainty controls the slope of the fragility function; the less random uncertainty, the steeper the fragility function becomes. As random uncertainty is reduced towards zero, the fragility "curve" approaches a step function with its break point at the fragility level of the component.

The 5% function and 95% function in Fig. 1-1 represent the "modeling uncertainty" in the median fragility function. These bounds, which may also be referred to as 5% and 95% confidence limits, are based on the assumption that there is uncertainty in the median capacity; this uncertainty is characterized by a logarithmic standard deviation β_U. Simply stated, the 95% confidence limit implies the following:

- there is only a 5% subjective probability ("confidence") that the actual fragility level is less than the median capacity indicated for the 95% fragility function.

- we are 95% confident that the "true" fragility function for the component would be equal to or greater than the 95% function.

Modeling uncertainty, often described as "lack of knowledge" about the component in question, reflects the adequacy (or inadequacy) of information -- component damping values, for example -- used by the fragility analyst to form his judgements about component capacity. Thus, modeling uncertainty in fragility descriptions has a subjective rather than a "random" basis as is true in the statistical sense.

For any given component, empirically developing a statistically meaningful seismic fragility would require that a large population of identical components (e.g., several hundred or several thousand) be subjected to successively higher levels of acceleration and the distribution of failures (however "failure" is defined) be recorded as a function of acceleration level. Practical constraints on time and resources clearly make this infeasible for a single component under well-defined load conditions, let alone for the effectively infinite combinations and permutations of component type, manufacturer, mounting, and loading conditions that could be identified for actual nuclear power plants. Therefore, an alternative approach is necessary to experimentally gain an insight into fragility.

Our approach to assessing fragility takes advantage of the fact that for practical PRA applications, a limited or "lower bound" fragility description may be adequate. In a probabilistic analysis, failure occurs only when the probability distributions of response and fragility overlap; therefore, only the lower tail end of the fragility curve may be of interest from a PRA standpoint. For components having a high seismic capacity (high "ruggedness"), the overlap of the response and fragility distributions could conceivably be so small under all credible loading conditions as to imply that the probability of failure is negligibly low.

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One method of developing a "lower bound" fragility is to estimate the so-called "HCLPF" (High Confidence, Low Probability of Failure) capacity for the component. The HCLPF capacity considers both the random and modeling uncertainty in the median capacity. The definition of HCLPF used in the CFRP is that adopted by the LLNL Seismic Design Margin Program, namely that value of the forcing or response function (such as seismic acceleration) for which we have "95% confidence" that the probability of "failure" is less than 5 percent.[2] According to this definition, if the median capacity of a component is defined by a peak acceleration with value A, the corresponding HCLPF capacity (i.e., HCLPF acceleration) is obtained from the following numerical relationship:

$$A_{HCLPF} = A \exp\left[-1.65\,(\beta_R + \beta_U)\right] \qquad (1\text{-}1)$$

where β_R and β_U represent the random and modeling uncertainties, respectively. The median capacity A can be determined by component tests, either to actual failure or to some threshold or "cut-off" limit. The cut-off might be applied, for example, in testing certain components whose actual median capacities were significantly above any response levels of regulatory interest.

The HCLPF capacity provides a practical means of addressing variations that inevitably arise between actual plant conditions and test conditions, variations that might otherwise be difficult to parametrically quantify by testing alone. For example, the random uncertainty β_R allows for variations in real earthquake motion compared to test input motion, variations in building floor response, or (e.g., for cabinet-mounted electrical devices) random variations in cabinet response. The modeling uncertainty β_U can account for variations in real damping values, or in component mounting conditions, or in the response of functionally similar components of different size or supplied by different manufacturers. These uncertainties can be quantified by systematically structuring test conditions in the form of "sensitivity studies" to investigating the effect of various parameters on the measured median capacity of the device tested. This was the basic approach taken in our Phase I demonstration tests.

The HCLPF approach has the added advantage that, in the absence of complete fragility data, a "lower bound" fragility can still be defined for a seismically qualified component by assuming its qualification level also represents its HCLPF capacity. Engineering judgement can then be applied to estimate the uncertainty parameters and thus make inferences about the median capacity.

Note that because the HCLPF capacity by definition presumes a five percent probability of failure, while "qualification" implies no failure, this approach tends to be conservative. It may in fact be overly conservative if qualification levels are low, as would be the case for many plants in the eastern United States. However, HCLPF capacities based on "high level" qualification data -- from plants in the western United States, for example -- can provide useful lower bound fragilities for plants having relatively low design basis earthquakes. Section 3 of this report describes how we used this approach to infer the actual capacity of selected electrical equipment.

In itself, the HCLPF capacity is a useful parameter on which to base regulatory decisions concerning seismic performance. However, extreme care must be exercised in selecting "reasonable" values of β_R and β_U when using a HCLPF capacity derived from qualification data to infer the actual capacity or "fragility level" of a component. The reasons for this are two-fold:

- as shown in Fig. 1-2, the slope of the fragility curve becomes more shallow as random uncertainty (β_R) increases. Therefore, the resultant median capacity on the 95% curve (and, for constant β_U, the inferred fragility level) also increases with increasing random uncertainty.

  As shown in Fig. 1-3, however, if the fragility level of the component is known (e.g., from actual failure tests), then the HCLPF capacity derived from the median capacity decreases with increasing random uncertainty.

- similarly, as modeling uncertainty (β_U) increases, the offset between the 95% fragility function and the 50% function also increases, implying an increase in the inferred fragility level. If, on the other hand, the fragility level is known, an increase in modeling uncertainty drives the HCLPF capacity towards lower (i.e., more conservative) values.

The above exercise illustrates how a "bottom-up" approach towards estimating median capacity (i.e., inferred from HCLPF capacity) can imply that fragility level increases with uncertainty, which is clearly non-conservative. This observation suggests that the reverse approach -- basing HCLPF capacities on measured fragility levels -- is preferable for assessing seismic performance. For a given fragility level, such a "top-down" approach yields lower (i.e., more conservative) HCLPF capacities as uncertainty increases.

1.5 Phase I Demonstration Tests

As part of the Phase I CFRP, we completed demonstration fragility tests on a three-column Westinghouse Five-Star motor control center containing 8 Westinghouse motor controllers of various types and sizes as well as 14 relays of different types and manufacturers. The Five-Star is the current basic model marketed by Westinghouse for industrial and power system applications; it is essentially identical to the Type W motor control center manufactured by Westinghouse from 1965 to 1975, various configurations of which are found in many nuclear power plants of this vintage. The particular electrical devices selected represented a sample of standard MCC devices typical in function of those found in actual plants, but are not necessarily generic for all similar devices.

To investigate the effect of base flexibility on the structural behavior of the MCC and on the functional behavior of the electrical devices, we conducted multiple tests on each of the following four mounting configurations: four bolts per column with top bracing, four bolts per column with no top bracing, four bolts per column with internal diagonal bracing, and two bolts per column with no top or internal bracing. We performed a total of 56 test runs, including 43 biaxial random motion tests (vertical plus one horizontal axis). Table input motions in the random motion tests ranged up to

2.5 g zero period acceleration (ZPA), which yielded in-cabinet spectral accelerations up to 10 g and higher at the device locations.

In these tests we investigated both the functional behavior of the individual electrical devices -- relays and starters -- and the structural response of the MCC cabinet for various levels of table input motion and for four different cabinet mounting configurations. Device "fragility" was characterized by contact chatter correlated to local in-cabinet response measured at the device location, with functional "failure" being defined as the first sign of chatter. We applied these experimental results to develop probabilistic fragility descriptions for each type of electrical device in the MCC, referencing fragility to local ZPA at the device location. In addition to "best estimate" descriptions of device fragility, we estimated the random variability and modeling uncertainty to arrive at a "high confidence, low probability of failure" (HCLPF) capacity for each type of device.

In these tests we also observed the structural behavior of the MCC cabinet for various levels of table input motion and for the different mounting configurations. Although substantial damage (cracked and broken welds) was observed in later tests, the cabinet nevertheless withstood some 20 strong motion tests at ZPA levels up to 1.9g before any significant damage was observed. In general, the results of our Phase I demonstration tests suggested the following:

- contact "chatter" appears to be influenced more by spectral acceleration than by ZPA, although the likelihood of chatter will, on the whole, increase with ZPA. Device fragilities based on spectral accelerations should in principle be "more appropriate" but at the same time would be more difficult to apply in a PRA.

- chatter appears to be influenced more by low-frequency input motion (i.e., less than 9 Hz) than by high-frequency motion. Consequently, frame resonances will affect device performance more than local "rattling" of the cabinet structure.

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- reed-type relays, which we did not observe to chatter at any time during our tests, appear to be more resistant to seismic motion than the more conventional armature-type relays.

- top bracing of the motor control center can increase the seismic capacity of both the MCC structure (by limiting cabinet motion) and the internal electrical devices (by increasing the resonant frequency of the cabinet frame).

Although independent of our prioritization efforts, the Phase I demonstration tests did provide guidance on the level of effort necessary to do meaningful yet cost-effective fragilities testing, as well as on the level of detail appropriate for specifying candidate components for Phase II evaluation.

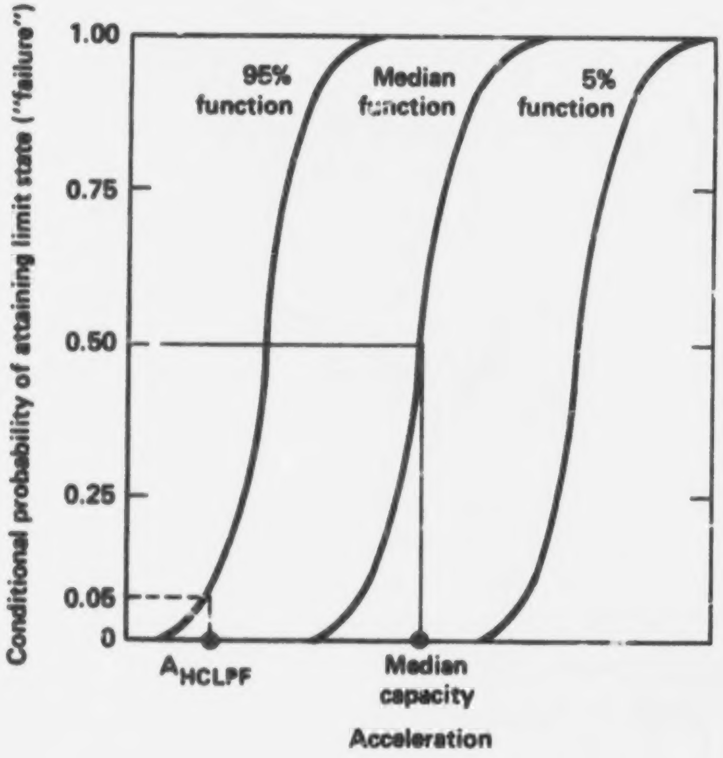

Figure 1-1. Typical curve set representing component fragility.

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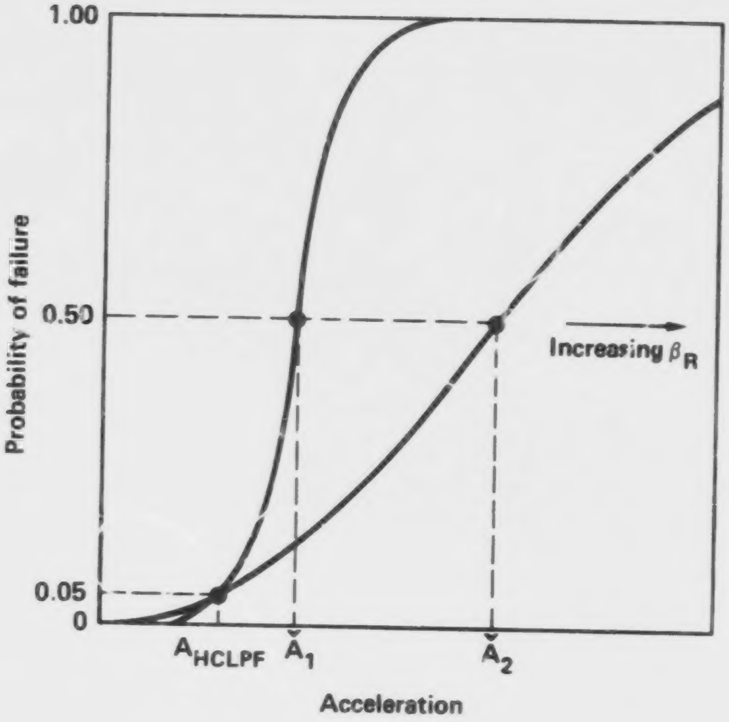

Fig. 1-2. Typical 95% fragility function showing how increasing random uncertainty affects median capacity derived from a HCLPF value. For constant β_U, the inferred fragility level of the component (i.e., median capacity of the 50% function) would be similarly affected.

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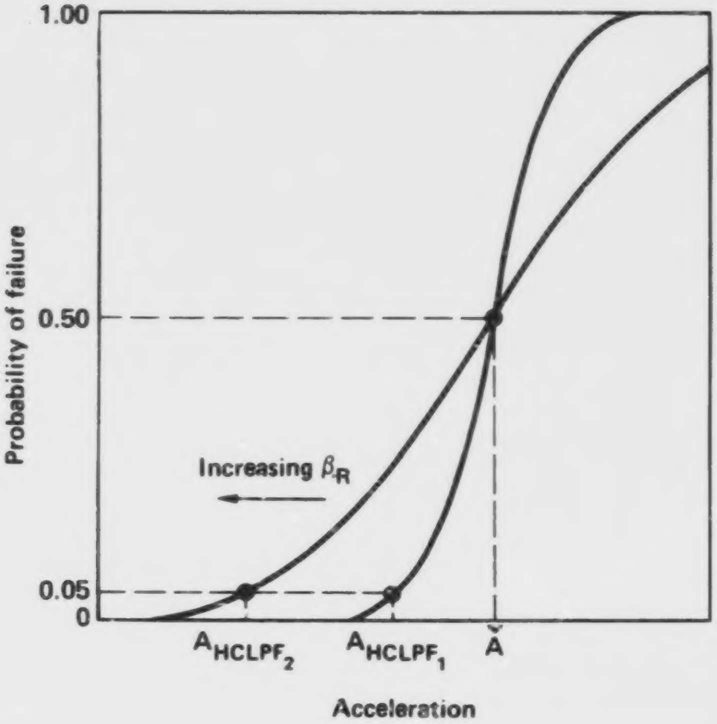

Fig. 1-3. Typical 95% fragility function showing how increasing random uncertainty affects the HCLPF value derived from a constant median capacity. For constant β_U, the effect would be the same for HCLPF values derived from a constant component fragility level.

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2. COMPONENT PRIORITIZATION

2.1 General Approach

In order to reduce to a manageable level the number of components included in a comprehensive test program, it was first necessary to review and prioritize components related to plant safety. Past efforts to develop generic minimum equipment lists through the use of probabilistic risk assessment models have met with limited success. The results of these efforts suggested that the apparent importance of components was strongly influenced by the component fragilities assumed in the analyses.

The results of such probabilistic analyses can also vary widely from plant to plant, being strongly influenced by the specific event trees and fault trees used in the analysis. The reasons for these variations include the following:

- event trees, which describe the postulated accident scenarios ("initiating events") potentially leading to core melt, depend on plant system design and operating procedures.

- fault trees, which describe the sequences of equipment failure leading to core melt given that an initiating event has occurred, similarly depend on plant system design. Of particular importance are such factors as redundancy (e.g., duplicate systems, multiple trains within a given system, multiple systems of different design but with the same safety function), effects of partial failure, the potential for "common-mode" failure (e.g., independent vs shared power sources), and the "fragility" of the components in these systems.

  When assessing the influence of fault trees on the apparent importance of certain components, it is also important to consider that component failure may not necessarily constitute a "failure" in a safety sense. For example, the safety significance of seismically-induced contact

18

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"chatter" -- uncommanded state changes -- in a motor controller would depend on electrical circuit design and the characteristics of the mechanical device (e.g., a pump motor) that the starter was connected to. Consequently, although a particular starter may have a certain fragility (e.g., defined on occurrence of chatter), its "importance" in a safety sense could be very different from one plant (or, for that matter, from one system) to the next.

For any given component or component type, its fragility -- or probability of failure -- will itself depend on many factors that may vary widely from plant-to-plant. These include the following:

- manufacturer-specific differences in design, as well as random variations in performance from component-to-component.
- the particular failure mode identified and its relationship to plant safety.
- the "external interface" between the component and its environment, primarily component mounting conditions.
- degradation ("aging") caused by such factors as temperature, vibration, and radiation.
- input load characteristics, which are influenced by site-specific soil behavior and structural response (e.g., component location) as well as to random variations in seismic input motion.

Clearly, feasibility considerations limit not only our ability to empirically develop broadly applicable "generic" fragilities, but to identify individual components as being "most important" to plant safety.

In view of these limitations, we took an alternate approach to systematically identify, categorize, and prioritize electrical and mechanical components. We based this approach primarily on the design of "typical" plant systems under both normal and abnormal operating conditions, supplemented by expert opinion on plant operating experience, past PRA results, and the results of industry qualification testing. The general approach taken in this effort, outlined by Fig. 2-1, proceeded in the following steps:

1. Identify "safety functions" necessary to maintain a plant in a safe condition ("normal operation"), or to safely bring the plant to and maintain it in a state of cold shutdown in the event of an earthquake ("accident mitigation").

2. For each safety function, identify associated plant systems (or subsystems, as appropriate). The systems considered included those having only a normal operating function, those having only a designated safety function (i.e., for accident mitigation), and those having both operating and safety functions.

3. For each system, list major components based on system descriptions. Here "components" included items generally regarded as mechanical or electrical equipment. Such items as piping, tanks, heat exchangers, equipment supports, and structures were not included.

4. Within each system, group components according to whether they are "very important", "important", or "less important" to the system being able to perform its designated safety function.

5. Within each system, identify "high-", "intermediate-", or "low-capacity" components based on the anticipated ability of each to function during a postulated earthquake.

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6. Rank each component by combining its importance and seismic capacity.

The specific criteria for defining importance and seismic capacity are outlined in the following sub-sections. As shown in Fig. 2-1, the general process resulted in nine natural groups, that is, three levels of seismic capacity for each importance group. Those components ranked as "very important, low-capacity" became first-priority candidates for Phase II testing, while "important, low-capacity" or "very important, intermediate-capacity" were assigned as second-priority candidates.

The actual systematic prioritization of components was performed by a Component Identification Working Group formed of expert consultants from a wide range of engineering disciplines. The working group members were drawn primarily from the nuclear industry, and represented a number of nuclear steam supply vendors, architect-engineering firms, and utility owner-operators.

Chaired by J. LaVallee of Power Consultants, this group was chartered to identify and rank components following the approach outlined above. After components had been subjectively ranked, the LLNL staff collected and evaluated industry data -- mainly results of qualification testing -- in order to substantiate these ranking groups or to identify discrepancies suggesting components for which further evaluation was warranted.

In addition, a Senior Consultant Group, chaired by D. Landers of Teledyne Engineering, was formed to review and comment on the overall approach and general assumptions employed within the context of the entire program. These included such topics as earthquake characterization and treatment of effects of aging or design and construction errors. Although not directly related to the prioritization effort, a second working group, the Component Testing Working Group, finalized the Phase I demonstration test procedures.

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2.2 General Assumptions

In the Component Fragility Research Program, we have made certain basic assumptions that have influenced both component prioritization and our Phase I demonstration tests. These include the following:

- *Characterization of seismic capacity*. We characterize earthquakes by their peak ground acceleration (PGA), taken to be the average value of the two horizontal components and assumed to occur on the soil free surface and at the top of the finished grade. To relate the seismic capacity of a component, however, we have chosen as our basis the local excitation at its support points, in other words, the floor response that it would see as a result of amplification by the structure. We defined as "high capacity" those components that would remain functional when subjected to local response spectra characterized by relatively broad-band frequency content and a 2g (or greater) zero period acceleration (ZPA). Using realistic definitions of earthquake ground motion and structural response prediction, this level of local response is expected to bound structural responses resulting from earthquakes inducing free field ground motions of up to 1g PGA. This value of PGA is about two times (or more) the maximum SSE of "regulatory interest" for plants located east of the Rocky Mountains.

  Note that this level also provides a useful threshold for test purposes, because practical lower bounds on fragility can be obtained without necessarily testing a component to destruction.

  Similarly, we defined as "intermediate capacity" components those that would be expected to "fail" (either functionally or physically) when subjected to local ZPA levels between 1g and 2g. "Low capacity" components would fail at local response levels less than 1g ZPA.

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- High frequency excitations. Although recent earthquake records confirm that high frequency components of ground motion can be present in the free field, the focus of the CFRP is on earthquake ground motions dominated by low-frequency ground motion, i.e., less than 9 Hz. Note, however, that this emphasis does not preclude recording high-frequency response data for components selected for Phase II testing, particularly if available information (e.g., qualification test data) indicates that high-frequency motions may significantly affect component behavior. In our demonstration tests, for example, we concentrated on low-frequency behavior, although some high-frequency response data were also recorded.

- Degraded components or behavior. At least three potential sources of physical component degradation or degraded behavior can be identified: design and construction errors, aging, and partial failure.

  For purposes of component prioritization, we assumed that the mechanical and electrical equipment reviewed had been properly designed, fabricated and installed. Although we did not explicitly include design and construction errors as a basis for developing a list of candidate components for Phase II testing, the potential for errors (e.g., vis-a-vis quality assurance or quality control procedures) serious enough to significantly reduce component capacity may have to be reviewed when structuring test conditions for individual components investigated in Phase II.

  In our demonstration tests, for example, the systematic variation of MCC base flexibility does provide insight into how improper cabinet mounting can affect the behavior of internal electrical devices.

  The behavior of aged components may be addressed in a limited fashion during Phase II, either directly (such as testing components removed from actual plant service) or by applying the results of aging test programs conducted by others.

We have not identified modes of partial failure for any of the components reviewed in our Phase I prioritization efforts, although the potential for partial system failure is taken into account. As in our demonstration tests, a definition of "failure" as it relates to a given component would be an integral part of the test procedures.

Deterministic vs Probabilistic Approach

A probabilistic approach is, of course, necessary when attempting to define fragility descriptions suitable for use in probabilistic risk assessments. However, because experience with the seismic performance of equipment is related deterministically (e.g., fragility "levels" rather than fragility "curves"), our prioritization efforts did not take the likelihood of failure (as implied by maintenance experience, for example) into account when assessing component importance or seismic capacity. The responsibility for "translating" deterministic experience into probabilistic fragility descriptions was left entirely to the LLNL staff.

2.3 General Conditions and Plant States

Development of a general importance list required postulating a specific earthquake scenario, as this affects the relative safety significance of different components. We postulated the following general conditions and plant states for this purposes of component prioritization:

- General conditions. Loss of offsite power is assumed to coincide with the occurrence of an earthquake. Some loss of reactor coolant inventory is assumed to occur, without regard for the source of the loss; combination of the effects of an earthquake and a large loss-of-coolant accident (LOCA) were not considered. The results of piping reliability research performed by LLNL in the Load Combination Research Program support the validity of this assumption.

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Operator action is considered to neither enhance nor degrade the availability of a system or component during or following a seismic event. Redundancy was also disregarded, both for systems within a plant and for components within a system.

- Plant states. Systems and components were assumed to affect one or more of the following plant states: cold shutdown (normal operation), accident mitigation (placing the plant in a cold shutdown condition following an accident), or other conditions relevant to plant safety but not directly needed to place the plant in a cold shutdown condition (e.g., fire protection).

Table 2-1 presents a list of typical systems or functions relevant to plant safety, together with the plant states they affect.

2.4 Development of Prioritization

The following discussion briefly describes how the Phase I component ranking was arrived at.

Plant Safety Functions

The following plant functions were assumed to contribute to plant safety, either during normal operation or accident mitigation, or both:

1. Control reactivity
2. Control reactor coolant inventory
3. Maintain integrity of the reactor coolant pressure boundary
4. Maintain adequate core cooling
5. Remove decay heat
6. Maintain plant environment
7. Maintain containment integrity
8. Maintain adequate supply of electrical power
9. Provide control and instrumentation
10. Maintain vital auxiliaries

Plant Safety Systems

Table 2-2 lists the plant systems considered in this evaluation, organized by safety function; Tables 2-3 through 2-12 provide for each safety function a system-by-system breakdown of the components considered in this evaluation. Where appropriate, plant "sub-systems" may be considered instead; for example, a "Safety Injection System" may include separate "subsystems" for high- and low-pressure injection, residual heat removal, and core spray. This list was based primarily on a review of system descriptions for the Zion plant operated by Commonwealth Edison of Illinois. Zion, a four-loop Westinghouse PWR plant, was selected as a case study because (1) the plant has been used as a basis for several past LLNL evaluations and therefore extensive detailed information is available in LLNL files, and (2) the Component Identification Working Group chairman (J. LaVallee) was formerly the Sargent & Lundy project engineer for Zion. As a result, the systems considered tend to be PWR-oriented, although certain systems unique to boiling water reactor (BWR) plants are considered as well. Despite the strong PWR emphasis, we regard the resultant prioritization of components as reasonably representative of all plants, due to the fact that the relative importance of systems -- which, as noted earlier, may vary widely from plant-to-plant -- is not taken into account.

Component Importance

For each system listed in Table 2-2, components were ranked according to their affect on the ability of that system to perform its intended safety function. No consideration was given to the relative importance of any one system compared to another, as this is highly variable from plant-to-plant. As discussed earlier, past attempts to use PRA techniques for defining "generic" importance lists have in fact indicated that the relative importance of plant systems is strongly dependent on the component fragilities assumed in the assessment.

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After components were identified for a particular system, each was assigned to one of three importance groups -- very important ("VI"), important ("I"), or less important ("LI") -- according to the following guidelines:

Very Important: failure of the component would prevent the system from performing its designated function. In other words, component failure implies system failure.

Important: failure of the component results in a significant reduction in system performance.

Less Important: failure of the component would not significantly affect the performance of the system.

Note that component "importance" or "safety significance" as used in this development is not intended to necessarily correspond with or to redefine equipment "important to safety" as used in NRC terminology. The assignment of a component to a particular importance group was based on the subjective judgement of the Component Identification Working Group members.

In principle, the relative importance of a given component (or type of component if more than one are present) to a particular system could be affected by redundancy and by component performance characteristics. For example, if a pump is able to deliver only 50% of its rated flow, the relative importance of that pump would depend on how the flow reduction affects the ability of the overall system to perform its function, taking into account such factors as number of flow trains and the discharge capacities of other pumps in the system. As noted earlier, however, our prioritization scheme recognized neither partial failure nor redundancy of components. The latter factor implies that common mode failure is an important consideration; therefore, even redundant components may be categorized as "very important."

The following example shows how components within a system, in this case the Zion residual heat removal (RHR) system, were ranked by their relative importance to overall system performance. As shown in Table 2-6, the Zion RHR system includes the following major components:

- Pumps and drives
- Motor-operated isolation valves
- Motor-operated flow control valves
- Air-operated flow control valves
- Swing check valves

The relative importance of these components to overall system performance was ranked as follows:

- Pumps and drives were considered "very important" because their operation would be necessary to provide coolant flow for residual heat removal. The normally-closed (NC) motor-operated valves isolate the RHR system from the reactor coolant system during normal operation and were therefore also considered "very important"; if they were to fail open during normal plant operation (e.g., due to earthquake-induced inertial loads), the RHR system (600 psi rating) would be subjected to the full pressure of the reactor coolant system. Conversely, if the valves were fail closed upon demand, coolant flow would be interrupted. Note that the former case could also occur if the valves were to inadvertently open due, for example, to a spurious "start" signal caused by earthquake-induced chatter in a control circuit.

- The motor-operated flow control valves and the normally-closed air-operated flow control valve would fail in an open position. If a valve were to fail, partial flow recirculation could result in the RHR system,

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thereby reducing coolant flow to the reactor. Because partial flow from the RHR system would still be available, these valves were ranked as "important".

- The normally-open (NO) air-operated flow control valves would fail in an open (i.e., safe) position. Therefore, these were ranked "less important". The swing check valves were also ranked "less important" because their failure would most likely occur in an open position.

The results of the importance ranking for the Zion RHR system can therefore be summarized as follows:

Very Important	Important	Less Important
Pumps and drives	MO FC valves	AO FC valves (NO)
MO isolation valves	AO FC valves (NC)	Check valves

Seismic Capacity

As discussed earlier, component seismic capacity was characterized by local zero period acceleration (ZPA) at the component support location. The local response spectrum was assumed to be characterized by a relatively broadband frequency content, with a ZPA of 2g (or greater) being postulated as an important threshold to denote "high capacity" components. For realistic definitions of earthquake ground motion and structural response, this local threshold (if considered as a structural floor response) is expected to encompass earthquakes inducing up to 1g peak ground acceleration (PGA) in the free field. For our purposes, three "capacity levels" were identified:

Level 1: component is expected to remain functional for local response greater than 2g ZPA ("high capacity").

Level 2: component "failure" is anticipated for local response between 1g and 2g ZPA inclusive ("intermediate capacity").

Level 3: component "failure" is anticipated for local response less than 1g ZPA ("low capacity").

where "failure" might be defined as either functional or physical failure, or both. Note that no detailed verification was undertaken of earthquake ground motions corresponding to Levels 1, 2, and 3 of local response, as this would depend on plant-specific structural and geological characteristics. Note also that the precise definition of "local response" depends on the particular mounting characteristics of the component in question. For example, the appropriate "local response" for motor control center (MCC) internals (e.g., relays, contactors) would be the in-cabinet response at each device location, while that for the MCC as a whole would be the structural "floor response" at the cabinet base.

Continuing with the RHR system example, the complete ranking of components by both component importance (VI, I, and LI) and seismic capacity (1, 2, or 3) is as follows:

System/Component	Importance Group	Capacity Level	Ranking Group
Residual Heat Removal System			
Pumps and drives	VI	1	VI-1
Motor-operated isolation valves	VI	1	VI-1
Motor-operated flow control valves	I	1	I-1
Air-operated flow control valves	LI	1	LI-1
Swing check valves	LI	1	LI-1

Note that all of the major components in the RHR system are ranked as "high" seismic capacity, that is, capable of remaining functional when subjected to local input motion of 2g ZPA.

Tables 2-13 through 2-15, respectively, summarize all low-, intermediate-, and high-capacity components identified in this evaluation, arranged according to importance group. Appendix A also summarizes these results in the form of a component-by-system matrix.

2.5 Comparison Against Data

After the reviewed components had been subjectively ranked by importance group and anticipated seismic capacity, a comparison was made with available qualification data as a check on the subjective seismic capacity level. The main source of data used for this purpose was a summary of qualification test results for Millstone Unit 3 (a Westinghouse PWR) provided by Northeast Utilities Company. This data was supplemented by similar data taken from a seismic re-evaluation program performed by the Pacific Gas & Electric Company for Diablo Canyon Units 1 and 2 (also a Westinghouse PWR) following discovery of the previously undetected "Hosgri" earthquake fault near the plant site.[3]

Note that the "qualification level" for a particular component relates its performance at a specific test input level which in turn reflects the design basis earthquake for the plant site. It is not the "fragility level" of the component, and may in fact be an overly conservative representation of the point at which component "failure" would actually occur.

The design of Millstone, located in Connecticut, was based on a 0.18g free field PGA safe shutdown earthquake. This value is reasonably typical of plant sites located east of the Rocky Mountains. By comparison, Diablo Canyon (located in southern California) was originally designed for a 0.4g SSE, which was later increased to the 0.75g level on which the Hosgri evaluation was based. The Hosgri SSE is of interest for our purposes because it almost certainly bounds (perhaps by a factor of two or more) any "reasonable" increase in SSE levels that may eventually result from resolution of the

31

Charleston issue. A review of such "high-level" qualification data could be sufficient to confirm, at least as a first estimate, that certain "standard" plant items (e.g., pumps, valves, motors) are indeed "high capacity" components. As discussed earlier, such data could also provide reasonable HCLPF capacities for probabilistic fragility descriptions applicable to eastern plants.

The following discussion illustrates why a review of qualification data alone may not be sufficient for assessing the ultimate seismic capacity of certain plant equipment. Continuing with the Zion RHR system example, a comparison of anticipated seismic capacity with that inferred by the Millstone qualification test data yields the following:

System/Component	Subjective Ranking	Qualification Level (ZPA) h v	Inferred Seismic Capacity	Source
Residual Heat Removal System				
Pumps and drives	VI-1	2.1g	1	Mill
MO isolation valves	VI-1	3g	1	Mill
MO flow ctrl valves	I-1	3g	1	Mill
AO flow ctrl valves	LI-1	2.1g	1	Mill
Swing check valves	n/a	n/a	n/a	

A master list of safety-related components for Millstone is included in Appendix B. Appendix C presents a complete comparative list of all the systems and components reviewed in our evaluation. In this particular example the components for which data was available were all qualified for input motions exceeding the 2g local ZPA threshold necessary for a Level 1 (i.e., "high") seismic capacity rating.

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Note in this case that the "high capacity" rating of the RHR system pumps and valves was supported by the Millstone qualification data despite the relatively low (0.18g) SSE requirement. Consequently, the subjective ranking of these components as "high capacity" appears to be reasonable. Not surprisingly, however, much of the Millstone qualification testing did not reach the 2g threshold ZPA that we had designated for Level 1 components owing to the low SSE requirement. The following example shows how comparing against "high level" qualification data -- in this case from the PG&E evaluation program for the 0.75g Hosgri SSE -- can infer markedly different seismic capacity levels.

System/Component	Subjective Ranking	Qualification Level (ZPA) h	Qualification Level (ZPA) v	Inferred Seismic Capacity	Source
On-Site DC Power					
Batteries	VI-2	0.25	0.15	3	Mill
		2.1	1.1	1	Hosgri
Battery racks	VI-2	3.0	0.65	1	Hosgri
Battery chargers	VI-2	0.25	0.15	3	Mill
		2.2	1.3	1	Hosgri
Inverters (DC to AC)	VI-2	1.5	1.0	2	Hosgri

The discrepancies in inferred seismic capacity more likely reflect test input rather than "actual" component capacity. If this is indeed the case, HCLPF capacities based on the low-level qualification data would clearly yield conservative -- perhaps overly conservative -- descriptions of component fragility. Conversely, if the "high-level" data can be shown to apply to equipment at the "low-level" plant site, then substantial margin between

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design basis and actual ultimate capacity would be demonstrated. Of course, the applicability of "high level" qualification data to plant equipment qualified for significantly lower SSE levels depends on the extent to which the equipment in the high-level tests was modified specifically to meet the higher SSE requirement as well as to other factors such as differences in mounting conditions.

It therefore remains to identify a suitable technical basis for resolving these discrepancies in inferred seismic performance. Two avenues are available for this purpose:

- detailed evaluation of existing data, preferably actual fragility data or, alternatively, high-level qualification data.
- fragility testing specifically structured to investigate the effects of various factors (e.g., mounting) on seismic performance.

In either case, the evaluation must address not only the "commonality" of like equipment at high- and low-level plant sites, but also specific factors (e.g., mounting) that potentially affect seismic performance. Typically, these factors are not systematically investigated as a part of qualification testing; any "sensitivity studies" performed during such tests generally arise out of necessity as equipment is modified in order to meet qualification requirements.

To demonstrate how "high-level" qualification testing can be used to assess ultimate seismic capacity, we assessed in detail five components subjected to actual tests as part of the Hosgri seismic evaluation performed by the Pacific Gas & Electric Company. The results of our assessment, described in Section 3 of this report, indicated that high-level qualification data can be used to infer ultimate capacity ("fragility level") provided that sufficient information is available from which to estimate how factors such as component mounting affect seismic performance. Our evaluation further indicated that many components included in the Hosgri evaluation were qualified in their standard commercial configurations or with relatively minor modifications. This result is encouraging because it suggests commonality among certain "standard" equipment items and therefore that high-level test results can be used to "confirm" seismic capacity levels -- at least for "high capacity" components -- assigned to like equipment at plants having lower SSE requirements.

However, as discussed in Section 1, such a "bottom-up" approach (i.e., fragility level estimated from HCLPF capacity) suggests that fragility level increases with uncertainty, which is clearly non-conservative. Extreme care must therefore be exercised in selecting the uncertainty parameters used to infer the component fragility level. As noted earlier, definitive information may however not be available on certain factors potentially affecting seismic performance, such as component mounting, as these factors are not usually investigated systematically during qualification testing. Consequently, the uncertainty parameters will tend to be highly subjective and, by necessity, highly conservative.

This result implies that a "top-down" approach -- estimating HCLPF capacities from actual failure data measured in fragility tests -- is preferable for assessing seismic performance, particularly when developing detailed fragility descriptions for low-capacity equipment.

2.6 Implications for Fragility Evaluation

The ranking of a given component affects not only the perceived urgency of detailed evaluation, but also the nature and depth of evaluation procedures appropriate for the component in question. These procedures include options of comprehensive testing, evaluation of existing data, or some combination of the two. The following discussion outlines a general evaluation strategy for "very important" components (i.e., those in ranking groups VI-1, VI-2, and VI-3). Depending on anticipated seismic capacity, this strategy takes one of the following forms:

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Low-Capacity (Level 3) Components

According to our general prioritization procedure, Group "VI-3" components are assigned highest priority for comprehensive Phase II evaluation. As a minimum, testing should be performed to aid in the interpretation of existing data and to systematically improve understanding of factors affecting seismic performance. Using our Phase I motor control center (MCC) tests as an example, "VI-3" components would typically be subjected to the following procedure:

1. Identify failure modes and select response parameter(s) on which to base the fragility description. Whenever possible, "single-parameter" fragilities are recommended over multi-parameter descriptions in order to simplify their application in probabilistic risk assessment.

   In our Phase I MCC tests, we concentrated on the functional behavior of the internal electrical devices (i.e., starters and relays). We defined "failure" as the onset of contact "chatter", and chose to use local zero period acceleration (i.e., at the in-cabinet location of the device) as the response parameter in the fragility description.

2. Specify areas of concern ("technical issues") that potentially affect seismic performance. These might include, but need not be limited to, variations in mounting, input motion, and component damping. Our MCC tests focussed on "base flexibility", that is, the effect that variations in cabinet mounting might have on the behavior of the internal electrical devices.

3. Review existing test data to (1) assess the suitability of the Level 3 classification, and to (2) determine if sufficient data exists on which to base a fragility description. For "low-capacity" equipment, this should require as a minimum actual "fragility level" data measured, for example, as a part of seismic qualification testing.

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4. Identify similarity among components to determine a representative component or sample of components for testing. To keep resource and time constraints within reasonable bounds, this sample will most likely not be "generic" in the strictest statistical sense, but should attempt to include significant variations in a given component type. For example, the relays included in our MCC tests included armature- and reed-type relays obtained from several different manufacturers; we do not, however, represent that the test results are generically applicable to all relays.

5. Develop test procedures and establish test sequence. In our MCC tests we investigated the effect of base flexibility by testing the MCC in four different mounting configurations, one of which included top bracing. Testing began with the most rigid configuration in order to minimize test-induced fatigue effects.

Intermediate-Capacity (Level 2) Components

In general, the approach taken towards these components would be the same as, but perhaps less rigorous than, that taken towards the Group VI-3 components. Note that according to our general approach, the steps applied to Group VI-2 components would be equally applicable to to "important, low-capacity" (Group I-3) components.

High-Capacity (Level 1) Components

1. Obtain equipment qualification test data (preferably "high-level" data) and other relevant technical information.

2. Review the suitability of the Level 1 capacity rating.

3. Document technical justification. If insufficient data exists to adequately justify the Level 1 rating, or if the equipment for which data

is available was modified extensively to improve its seismic performance, limited "fragility level" testing may be desirable to confirm the high-capacity rating.

As discussed earlier, "high-level" excitation data is most appropriate for this purpose because it would be more likely to represent actual component behavior rather than test input. We anticipate that detailed assessment of such data would result in some readjustment of ranking groups as discrepancies between "actual" and subjective capacities were resolved. Note however we did not readjust our Phase I rankings, either to conform with higher capacities inferred by the Hosgri data (which may reflect specific hardware modifications to improve seismic performance) or lower capacities inferred by the Millstone data (which may reflect the low-level SSE requirement).

For components in the remaining ranking groups (i.e., I-2 and I-1; LI-1,-2,-3), equivalent data should be reviewed to substantiate the subjective capacity levels identified during Phase I. If, particularly for components subjectively rated as "high" capacity, we are unable to substantiate the capacity levels through comparisons with existing data, these components may become candidates (albeit lower-priority ones) for future testing.

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38

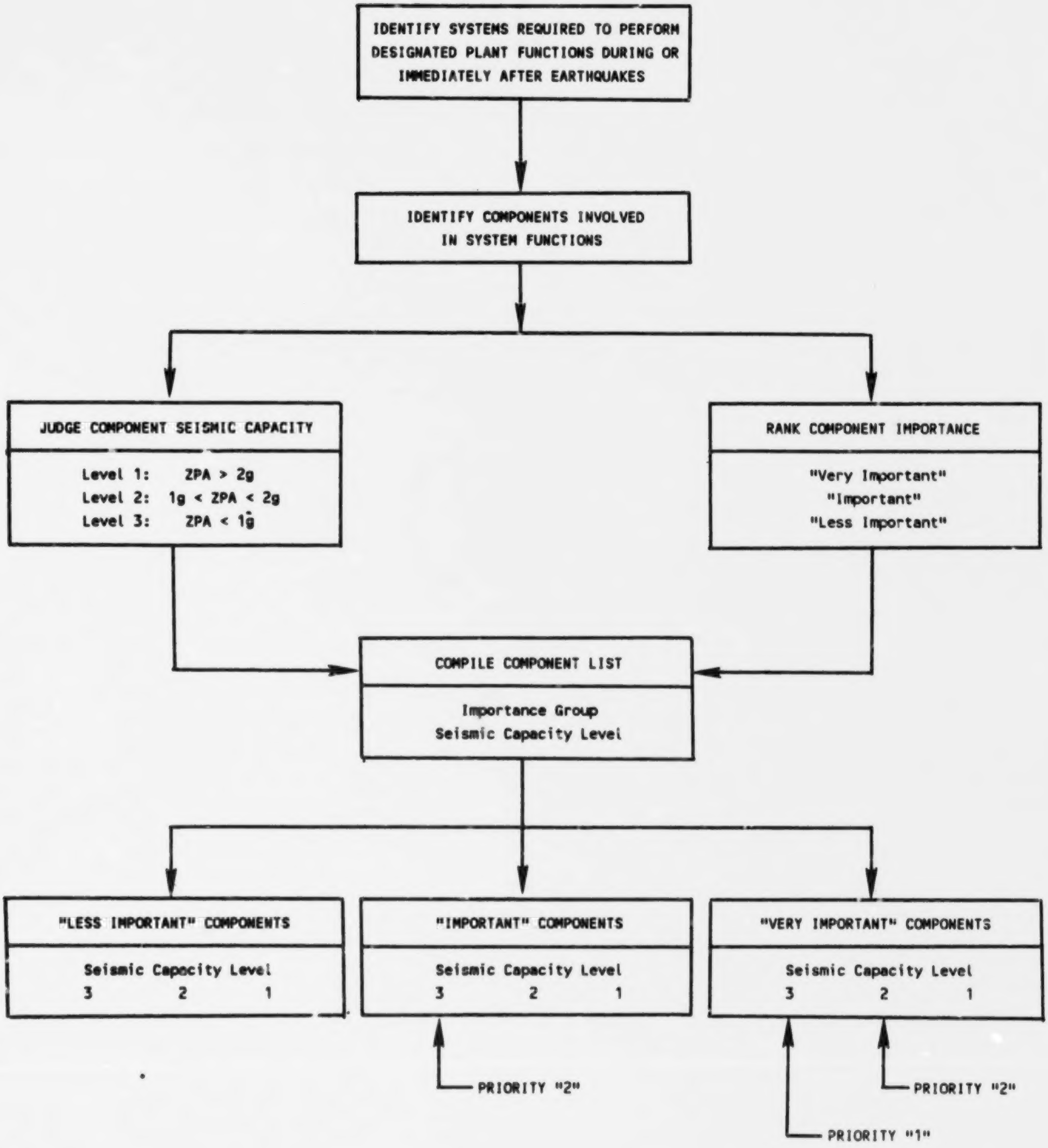
IDENTIFY SYSTEMS REQUIRED TO PERFORM DESIGNATED PLANT FUNCTIONS DURING OR IMMEDIATELY AFTER EARTHQUAKES
IDENTIFY COMPONENTS INVOLVED IN SYSTEM FUNCTIONS
JUDGE COMPONENT SEISMIC CAPACITY
Level 1: ZPA > 2g
Level 2: 1g < ZPA < 2g
Level 3: ZPA < 1g
RANK COMPONENT IMPORTANCE
"Very Important"
"Important"
"Less Important"
COMPILE COMPONENT LIST
Importance Group
Seismic Capacity Level
"LESS IMPORTANT" COMPONENTS
Seismic Capacity Level
3 2 1
"IMPORTANT" COMPONENTS
Seismic Capacity Level
3 2 1
"VERY IMPORTANT" COMPONENTS
Seismic Capacity Level
3 2 1
PRIORITY "2"
PRIORITY "2"
PRIORITY "1"

Fig. 2-1. General approach for component prioritization.

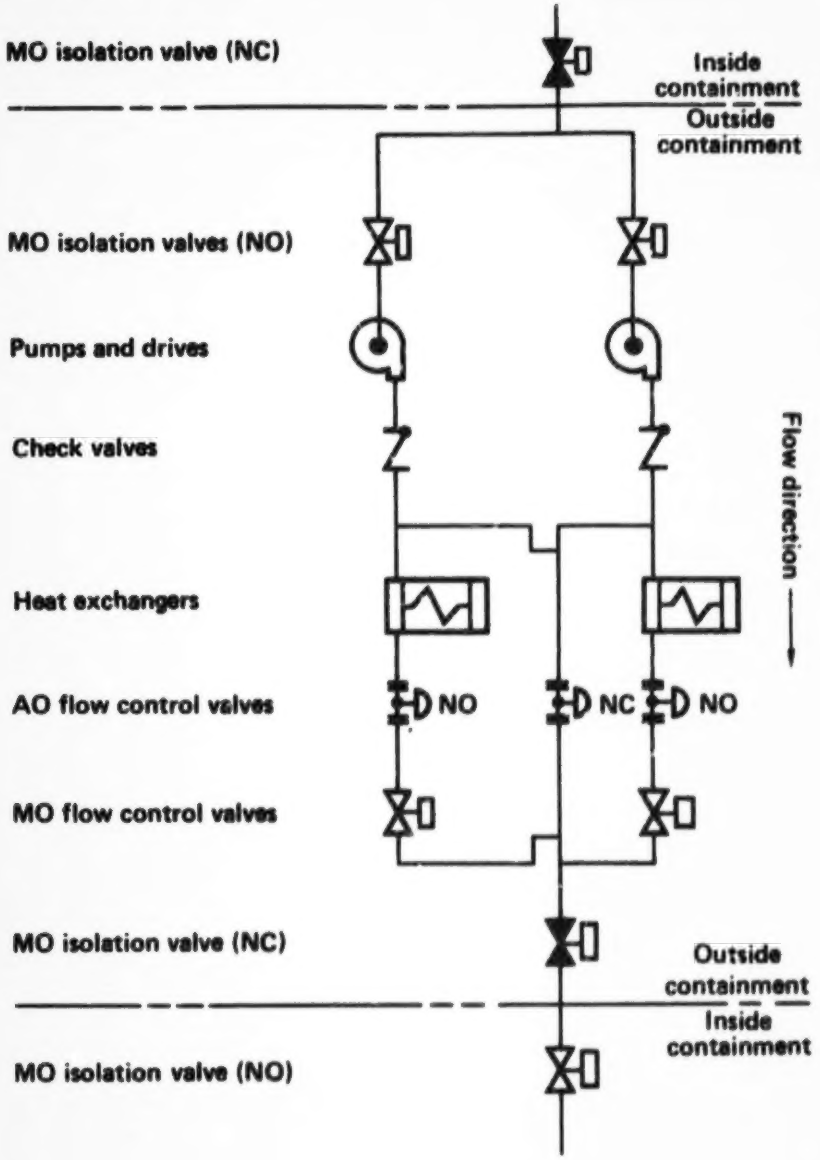
MO isolation valve (NC)
Inside containment
Outside containment
MO isolation valves (NO)
Pumps and drives
Check valves
Flow direction
Heat exchangers
AO flow control valves
NO
NC
NO
MO flow control valves
MO isolation valve (NC)
Outside containment
Inside containment
MO isolation valve (NO)

Fig. 2-2. Flow diagram of Zion residual heat removal system.

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40

Table 2-1. Systems or functions required to maintain plant safety.

Function or System	Cold Shutdown	Accident Mitigation	Other
Control Rod Insertion	x	x	
Charging	x	x	
Residual Heat Removal	x	x	
Service Water	x	x	
Component Cooling	x	x	
Main Steam/RCS Pressure Relief	x	x	
Auxiliary Feedwater	x	x	
Nuclear Instrumentation System	x	x	
Diesel Oil	x	x	
Emergency Diesel Generators	x	x	
AC/DC Power	x	x	
HVAC	x	x	
Safety Injection		x	
Core Spray		x	
Containment Isolation		x	
Containment Spray		x	
RCFC		x	
Isolation Valve Seal Water		x	
Penetration Pressurization		x	
RPS/ESF Actuation		x	
Purge			x
Radiation Monitoring			x
Chilled Water			x
Fire Protection			x

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41

Table 2-2. Systems identified according to plant safety function.

---

1. Reactivity Control

    1.1 Control Rod Insertion
    1.2 Accident Boration

2. Reactor Coolant Inventory Control

    2.1 Chemical and Volume Control System

        - Letdown
        - Charging (seal injection)

    2.2 Safety Injection Systems

        - High-head injection
        - Low-head injection
        - Residual heat removal
        - Core spray

    2.3 Reactor Coolant System (RCS) Pressure Relief

3. Reactor Coolant Pressure Boundary Integrity

    3.1 Reactor Coolant System
    3.2 RCS Pressure Relief System

4. Core Cooling

    4.1 Safety Injection Systems
    4.2 Residual Heat Removal System
    4.3 Main Steam (MS) System

5. Decay Heat Removal

    5.1 Auxiliary Feedwater System
    5.2 Reactor Coolant System
    5.3 RCS/MS Pressure Relief Systems
    5.4 Residual Heat Removal System

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42

Table 2-2 (cont.). Systems identified according to plant safety function.

---

6. Plant Environment
   - 6.1 Containment Spray System
   - 6.2 Reactor Containment Fan Coolers
   - 6.3 Heating, Ventilating and Air Conditioning (HVAC) Systems
   - 6.4 Containment Purge System
   - 6.5 Containment Refrigeration System (ice condenser plants)

7. Containment Integrity
   - 7.1 Containment Isolation System
   - 7.2 Containment Spray System
   - 7.3 Containment Ventilation Systems
   - 7.4 Isolation Valve Seal Water System
   - 7.5 Penetration Pressurization System

8. Onsite Electrical Power
   - 8.1 Onsite AC Power System
   - 8.2 Onsite DC Power System

9. Instrumentation and Controls
   - 9.1 Instrument Air System
   - 9.2 Nuclear Instrumentation System (ex-core)
   - 9.3 Control Panels and Boards
   - 9.4 Local Instrumentation Racks
   - 9.5 Local Instruments
   - 9.6 Radiation Monitoring System
   - 9.7 Reactor Protection System
   - 9.8 Emergency Safety Function Sequencing System

10. Maintain Vital Auxiliaries
    - 10.1 Closed/Component Coolant Water System
    - 10.2 Service Water System
    - 10.3 Chilled Water System
    - 10.4 Fire Protection System

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Table 2-3. Components reviewed for reactivity control.

1.1 Control Rod Insertion

- Control element drive mechanisms (CEDMs)
- CEDM motor-generator sets
- Reactor trip breakers
- Rod position indicators
- Rod bottom indicators

1.2 Accident Boration

- Charging pumps
- Motor-operated valves
- Check valves
- Explosive valves (BWR)
- Pressure relief valves (BWR)

Table 2-4. Components reviewed for reactor coolant inventory control.

2.1 Chemical and Volume Control System (Letdown)

- Air-operated flow control valves
- Reactor coolant filters
- Isolation valves

Chemical and Volume Control System (Charging - Seal Injection)

- Air-operated flow control valves
- Seal injection filters
- Charging pumps

2.2 Safety Injection Systems (All)

- High-pressure injection pumps and drives
- Low-pressure injection pumps and drives
- Motor-operated valves
- Check valves
- Vacuum relief valves
- Residual heat removal pumps and drives
- Core spray pumps and drives

3. Reactor Coolant System (RCS) Pressure Relief

- Power-operated relief valves
- Motor-operated valves
- Safety valves (PWR)
- Safety valves (BWR)

Table 2-5. Components reviewed for maintaining reactor coolant pressure boundary integrity.

3.1 Reactor Coolant System

- Electrically-operated solenoid valves
- Air-operated solenoid valves
- Reactor coolant pump seals
- Main steam isolation valve (BWR)
- Swing check valves (peripheral piping)

3.2 RCS Pressure Relief System

- Power-operated relief valves
- Motor-operated valves
- Safety valves (PWR)
- Safety valves (BWR)

Table 2-6. Components reviewed for core cooling.

4.1 Safety Injection Systems (see Table 2-5)

4.2 Residual Heat Removal System

- Pumps and drives
- Motor-operated valves
- Motor-operated flow control valves
- Air-operated flow control valves
- Swing check valves

4.3 Main Steam System

- Safety valves

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Table 2-6. Components reviewed for providing core cooling.

4.1 Safety Injection System (see Table 2-4)

4.2 Residual Heat Removal System

- Pumps and drives
- Motor-operated valves
- Motor-operated flow control valves
- Air-operated flow control valves
- Swing check valves

4.3 Main Steam System

- Safety valves

Table 2-7. Components reviewed for decay heat removal.

5.1 Auxiliary Feedwater System

- Pumps and drives (electric, diesel, turbine)
- Motor-operated valves
- Air-operated flow control valves
- Swing check valves

5.2 Reactor Coolant System (see Table 2-5)

5.3 RCS/MS Pressure Relief Systems

- Power-operated relief valves (atmospheric dump valves)
- Power-operated relief valves (isolation valves)
- Safety valves

5.4 Residual Heat Removal System (see Table 2-6)

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Table 2-8. Components reviewed for maintaining plant environment.

6.1 Containment Spray System

- Containment spray pumps and drives
- Motor-operated valves

6.2 Containment Fan Coolers

- Cooling water coils
- Chilled water coils
- Fans and drives
- Louvers
- Dampers

6.3 HVAC Systems

- Supply fans and drives
- Exhaust fans and drives
- Cubicle coolers
- Air-handling units
- Dampers
- Filters
- Butterfly valves

6.4 Containment Purge System

- Supply fans and drives
- Exhaust fans and drives
- Butterfly valves
- Filters

6.5 Containment Refrigeration System (Ice Condenser Plants)

- Refrigeration units
- Louvers and operators

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Table 2-9. Components reviewed for maintaining containment integrity.

7.1 Containment Isolation System

Motor-operated valves
Air-operated valves
Butterfly valves

7.2 Containment Spray System (see Table 2-8)

7.3 Containment Fan Coolers (see Table 2-8)

7.4 Isolation Valve Seal Water System

Air-operated pressure control valves
Swing check valves

7.5 Penetration Pressurization System

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Table 2-10. Components reviewed for maintaining onsite electrical power.

8.1 Onsite AC Power System

Diesel generators
Diesel oil systems (piping, pumps, valves)
Air starting systems
Lubrication oil systems
Combustion air intake louvers
ESF sequencers
Motor control center internals
Switchgear internals
Isolation amplifiers
Connection/mounting hardware
Transformers
Gas turbine

8.2 Onsite DC Power System

Station batteries (including mounting)
Battery racks
Battery chargers
Inverters (DC to AC)
DC distribution switchboard internals
Motor control center internals

Table 2-11. Components reviewed for providing instrumentation and control.

Radiation monitoring equipment
ESF/RPS actuation cabinet internals
Local instrument racks
Control panel/board internals
Nuclear instrumentation equipment (ex-core)
Limit switches
Electrical distribution equipment
Ion chamber electrical connections
ΔP/P transmitters
ΔP/P switches
Temperature switches
Flow switches
Relays
Process control equipment
Mechanical/electrical interlocks
Bistables
Indicators/power supplies
ESF sequencers
Motor control center internals
Switchgear internals
DC distribution switchgear internals
Air compressors

Table 2-12. Components reviewed for maintaining vital auxiliaries.

10.1 Closed/Component Coolant Water System

- Pumps and drives
- Motor-operated valves

10.2 Service Water System

- Pumps and drives
- Motor-operated valves
- Butterfly valves
- Strainers

10.3 Chilled Water System

10.4 Fire Protection System

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Table 2-13. Summary of components ranked as "low-capacity" (Capacity Group 3).

"Very Important" Components (Group VI-3)

- ESF sequencers
- Switchgear internals
- Motor control center internals
- Connections/mounting
- DC distribution switchboard internals
- Nuclear instrumentation equipment (ex-core)
- Electrical distribution equipment
- Ion chamber electrical connections
- ΔP/P transducers
- ΔP/P switches
- Temperature switches
- Flow switches
- Relays
- Process control equipment
- Mechanical/electrical interlocks
- Bistables
- Indicators/power supplies

"Important" Components (Group I-3)

- None identified

"Less Important" Components (Group LI-3)

- Rod bottom indicators
- Air handling units

54

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Table 2-14. Summary of components ranked as "intermediate-capacity" (Capacity Group 2).

"Very Important" Components (Group VI-2)

- Reactor trip breakers
- Pilot-operated relief valves
- Safety valves
- Atmospheric dump valves
- Motor control center internals
- Batteries/battery racks
- ESF/RPS actuation cabinet internals
- Local instrument racks
- Control panels/boards internals
- Limit switches
- Air compressors
- Bearing cooling system equipment
- Fire detection devices
- Fire deluge equipment

"Important" Components (Group I-2)

- Seal injection filters
- Pressure relief valves (BWR)
- Vacuum relief valves
- Reactor coolant pump seals
- Louvers
- Air filters
- Radiation monitoring equipment
- Chiller units
- Strainers

"Less Important" Components (Group LI-2)

- Rod bottom indicators
- Dampers

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55

Table 2-15. Summary of components ranked as "high-capacity" (Capacity Group 1).

"Very Important" Components (Group VI-1)

- Control rod drive equipment (BWR)
- Charging pumps and drives
- Motor-operated valves
- Check valves
- Explosive valves (BWR)
- Air-operated flow control valves
- Isolation valves
- Safety injection pumps and drives
- Residual heat removal pumps and drives
- Core spray pumps and drives
- Air-operated solenoid valves
- Main steam isolation valves
- Motor-operated flow control valves
- Auxiliary feedwater pumps and drives
- Containment spray pumps and drives
- Exhaust fans and drives
- Component cooling water pumps and drives
- Butterfly valves
- Air-operated valves
- Air-operated pressure control valves
- Diesel generators
- Diesel oil pumps and valves
- Diesel air accumulator
- Diesel lube oil equipment
- Combustion air intake louvers
- Isolation amplifiers
- Transformers
- Inverters

"Important" Components (Group I-1)

- Supply fans and valves

"Less Important" Components (Group LI-1)

- None identified

3. FRAGILITY DEVELOPMENT FROM "HIGH-LEVEL" QUALIFICATION DATA

3.1 General Discussion

As discussed earlier, using qualification levels to define HCLPF capacities may be overly conservative, particularly if low-level design basis earthquakes are involved. This problem can be avoided to some extent by using "high-level" qualification data as a basis for describing component fragility. This section describes an application of such data for five components at the Diablo Canyon nuclear power plant operated by the Pacific Gas & Electric Company. Diablo Canyon, located in southern California, was originally designed for a 0.4g PGA safe shutdown earthquake, which was later increased to 0.75g PGA upon discovery of a previously undetected offshore fault zone passing within a few miles of the plant site (the "Hosgri" fault). An extensive evaluation performed by PG&E and its consultants demonstrated that, with some modifications, equipment required to shut down and maintain the plant in a safe condition would be available following the postulated Hosgri earthquake. The LLNL fragility evaluation described in this section is based on "high-level" qualification data generated as part of the PG&E study.

The PG&E data is of interest for "low-level" sites east of the Rocky Mountains because the Hosgri input motions almost certainly bound any "reasonable" increase in SSE levels resulting from resolution of the Charleston issue. Although less definitive than actual failure ("fragility level") data for assessing ultimate section performance, high-level qualification data can be useful in the following ways:

- if equipment commonality can be shown between high- and low-level plant sites -- use of standard commercial items, for example -- the fragilities derived from "high-level" data may be directly applicable to equipment qualified for lower earthquake levels. The degree of commonality would, of course, depend in large part on the extent to which the tested equipment had been modified to meet the more stringent seismic qualification requirement. Evaluation of high-level data is most useful

57

for confirming "high" seismic capacity, less so when a more definitive fragility description is desired (e.g., for low-capacity components).

- if the tested equipment had been modified to meet qualification requirements, the test experience may suggest similar modifications that could be made to increase the seismic capacity of like components. These results can also provide guidance for development of seismic review ("walkdown") procedures for in-situ inspection of plant equipment.
- if commonality cannot be established, the "high-level" testing experience may suggest conditions for rigorous testing of the component in question.

It is important to note that we do not view evaluation of qualification data as a substitute for testing if truly definitive fragility descriptions are desired. Typically, qualification tests do not include systematic (i.e., parametric) investigations of factors that potentially affect seismic performance -- mounting conditions, for example. Any "sensitivity studies" during such tests usually arise out of necessity as equipment is modified to meet qualification requirements. As a result, often only minimal detailed information is available for estimating the uncertainty parameters needed to develop a complete fragility description.

However, in cases where "threshold" fragilities might be adequate for making regulatory decisions -- those involving "high capacity" components, for example -- high-level qualification data may provide reasonable HCLPF capacities and thus avoid or minimize new testing. Fragility curves derived from such data (i.e., by a HCLPF approach) can also provide serviceable PRA input if their high inherent uncertainty can be tolerated. Such might be the case, for example, if only the lower portion of the fragility curve were needed in a probabilistic risk assessment.

This section describes our detailed assessment of seismic capacity for five components included in the PG&E seismic reevaluation, including fragility curve development by the HCLPF approach discussed in Section 1 of this report. The following components were considered:

- 4160-volt metal-clad switchgear
- Safeguard relay boards
- Potential transformers
- Emergency light battery pack
- Station battery and racks

We selected these particular components for our purposes because they were actually retested as part of the Hosgri evaluation. The PG&E study found that many of the safety-related components at Diablo Canyon were originally designed with sufficient margin to meet the more stringent Hosgri criteria and therefore did not have to be requalified by test. For each of the five components that we examined, we provide the following:

- a general description of the equipment tested and its intended safety function.

- a discussion of major seismic failure modes and modifications made, if any, to improve seismic performance.

- the results of qualification testing for the 0.75g Hosgri earthquake.

- development of fragility curves, including all pertinent assumptions on which they are based.

3.2 4160-Volt Metal-Clad Switchgear

Description of Equipment

The 4160-volt ("4kV") switchgear that we examined is metal-clad, of the vertical-lift type, and is rated at 250 MVA interrupting capacity and 80,000 A momentary.[2] It is built up from three bus sections, each about 78 inches high, 24 inches wide, and 72 inches deep weighing approximately 3500 pounds.

The circuit breakers weigh over 2000 lbs each and are located in individual cells separated from each other by a metal barrier. The breakers are not supported at the base of the switchgear but instead ride on side supports which are raised and lowered by a screw mechanism. Doors in the front of each bus section provide access to the individual breakers and control wiring, doors in the rear provide access to the 4kV power connections. Protective relays, meters, control switches, indicator lights, auxiliary relays and voltage relays are mounted on the upper portion of the front doors. Potential transformers, originally mounted on top of the bus sections, sense feeder or bus voltages for instrumentation and control purposes. The bus sections are interconnected by overhead bus ducts, which do not have a seismic Class 1E function.

When installed in-plant, the switchgear is mounted so as to maximize structural rigidity. This mounting condition, achieved by welding the bus sections to the floor and by top-bolting to a suitable structural member, minimizes the amplitudes of expected seismic vibration in relays, breakers, and other sensitive internal devices. This condition was duplicated during the requalification testing.

Safety Function

The 4kV switchgear controls and distributes electric power to the engineered safeguard loads. The required safety functions of the individual devices are as follows:[3]

(a) The power circuit breakers switch the 4kV power on or off. The power includes the incoming power from one of three sources: the station auxiliary transformer, the stand-by start-up transformer, and, if necessary, the diesel generator, and the outgoing power for the engineered safeguard loads. The breakers must operate during a seismic event if required to do so, and must not change state inadvertently at any time.

(b) The overcurrent relays must not cause the circuit breaker to trip inadvertently at any time. It is the most important device from the safety function point of view. Figure 3-3 shows a typical overcurrent relay.

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(c) The potential transformers must stay operative at all times and provide a signal for control and instrumentation that is proportional to the level of the high voltage bus or feeder to which they are connected. While the transformer itself has no moving part which could compromise this safety feature, the contact fingers connecting the transformer windings to the high voltage and low voltage terminals must stay closed at all times.

(d) The voltage relays must sense the signal voltage of the potential transformers to which they are connected. Their contacts must open or close as required at any time. Contact chatter must not prevent downstream devices from operating and conversely must not operate downstream devices inadvertently.

(e) The 2HH9 timing relay closes the breaker after time delay on a safety injection signal. It must operate during or after a seismic event.

Seismic Failure Modes

The switchgear under consideration has been subjected to extensive dynamic tests carried out in laboratories with a shaking table. The dynamic tests indicate that the cabinet, even with structural modifications to enhance seismic capacity, still appears flexible for horizontal vibrations judging from the observed natural frequency. This is apparently due to the heavy breakers being side-supported above the base of the cabinet. However, the structural integrity of the switchgear did not appear to be in question and, consequently, is not the potential governing failure mode. The potential failure modes essentially pertain to the functional operability of the electrical relays and circuit breakers. In our judgment, the potential governing failure modes of the 4kV switchgear, listed in a descending order of vulnerability to seismic environments, are as follows (Refs. 3 and 4):

(1) Inadvertent chattering in the overcurrent relays that could spuriously close the electrical contacts and causes inadvertent trip in the circuit breakers. There are two types of moving elements in the overcurrent

relay, i.e., a time overcurrent induction disc element, and one to two seal-in units (Fig. 3-4). The induction disc is a rotating element essentially balanced in the horizontal plane and therefore not sensitive to horizontal vibrations. Vertical vibrations would also have no effect on the induction disc assembly because it cannot move in the vertical direction. The seal-in units are small hinged-armature relays located in the horizontal plane. The axis of rotation of the hinged armature is in the side-to-side direction and the only motion of the contacts is in the vertical direction because the armature piece is not balanced about its axis of rotation. By the nature of the armature construction and the design of the assembly, it is not expected to be sensitive to horizontal accelerations, but sensitive only to a threshold vertical acceleration acting upward on the unbalanced mass to overcome the downward restraining spring reaction. In summary, the seal-in unit in an overcurrent relay is sensitive only to the vertical seismic acceleration level, less sensitive to front-to-back vibrations, and least sensitive to side-to-side vibrations. The induction disc is not very sensitive to either horizontal or vertical vibrations.

(2) Inadvertent chattering in the undervoltage relay. Because it is of similar design as the overcurrent relay and has the same two types of moving parts, its vulnerability to seismic vibrations is essentially comparable to that of the overcurrent relay.

(3) Spurious chatter or change of state in the contacts of the auxiliary switch which is operated by the circuit breaker mechanism. However, the chatter of the auxiliary switch has no significant effect on the safety function.

(4) Inadvertent chatter or change of state in the timing relay. However, the dynamic tests demonstrated that chatter in the timing relay would not prevent it from performing its safety function.

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(5) Inadvertent chatter in the primary contacts of the power circuit breakers. However, the dynamic tests demonstrated that for standard circuit breakers rated 1000 volts and above the magnetic forces acting on the primary contacts would far exceed the seismic forces such that chatter in the primary contacts of the power circuit breaker is unlikely.

In conclusion, the only seismically sensitive devices in the switchgear are the overcurrent and undervoltage relays. Dynamic tests indicated that chattering in the other relays and devices such as the bus undervoltage auxiliary relay and start-up auto close relay would not prevent the switchgear from performing its safety function.

Modifications to Improve Seismic Performance

The switchgear in its commercial configuration (and with the rigid mounting conditions described above) was qualified for the original 0.4g Diablo Canyon SSE. It did not, however, satisfactorily meet the more stringent Hosgri requirements when first subjected to requalification testing. A detailed review of the switchgear structure and its electrical internals followed, resulting in several modifications being made to increase structural rigidity and thereby improve seismic performance. The major modifications made in the original commercial configuration of the switchgear included the following:

- increasing the sectional rigidity of the vertical elements of the switchgear frame. This was done by converting the original angle sections in the frame to square-tube sections through addition of new steel.

- adding steel stiffener plates in the side-to-side direction at the bottom and mid-plane elevations of the cabinet.

- bolting the door panels to the cabinet to make them a part of the structural elements, thereby eliminating door rattling and its associated high-frequency loading.

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- dynamically decoupling the overhead bus ducts from the switchgear bus sections. This was done by replacing the original rigid bus connection at the entry point into the switchgear with a flexible earthquake joint. This flexible joint is designed to accommodate the anticipated seismic deflections at the top of the switchgear.

- to lower the switchgear center-of-gravity, removing the massive potential transformer from the top of the cabinet and remounting it on the floor. This required that the transformer later be qualified separately, which had not originally been the case.

The structural modifications and rigid in-plant mounting conditions, as well as removal of the potential transformers and insertion of the flexible seismic joints, combined to maximize the structural rigidity of the switchgear. It should be noted that these modifications were implemented not out of concern for structural integrity, but rather for enhancing the seismic performance of the sensitive internal electrical devices.

Seismic Qualification

The 4kV switchgear was seismically qualified for the SSE by means of extensive dynamic tests. The dynamic tests were carried out on a shaking table capable of producing bi-directional (vertical and one horizontal) excitations. As shown in Fig. 3-1, all three bus sections were simultaneously tested at each time, to simulate the in-plant service condition.

For the SSE level qualification tests, the typical horizontal test motion is a multiple-frequency random motion. The typical vertical SSE level shaking table test motion is a multiple-frequency random motion superimposed with a sine beat motion. The sine beat motion was included to simulate the narrow-band dynamic amplification of the turbine building floor on which the switchgear is located. The test motions and setup conformed to the typical requirements of the 1975 IEEE-344 standard. Mounting of the switchgear on the shaking table simulated the in-plant service condition. Electrical states and functional operability of the various relays and control devices were

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monitored before, during, and after each test. Details of the dynamic tests and results are given in Ref. 5 as well as summarized in Ref. 3.

During the tests, the horizontal and vertical motions were recorded by accelerometers located not only at the shake table for monitoring the test motions, but also at thirteen other locations on the switchgear for monitoring the response motions. Figure 3-5 illustrates the accelerometer locations on the switchgear. Note that Location 13 corresponds to an overcurrent relay rigidly attached to the shake table, away from the switchgear, for the purpose of independent evaluation. The arrangement of the accelerometers enabled monitoring of both the test motions and response motions. The response spectra of the recorded motions were then computed. As an illustration, the 5% damping response spectrum of the test motions, i.e., the TRS (test motion response spectrum) for Test Run 16 (side-to-side and vertical) is shown in Figs. 3-6 and 3-7 for the horizontal (side-to-side) and vertical components, respectively. The corresponding 5% damping response spectrum of the response motions at, say, Location 7 on the switchgear is also shown in Figs. 3-6 and 3-7 for the side-to-side and vertical components, respectively. Similarly, Figs. 3-8 and 3-9 illustrate the 5% damping TRS for the front-to-back and vertical test motions, respectively, in Run 31, and the corresponding response spectra of the front-to-back and vertical response motions at Location 7 on the switchgear.

Comparing the spectra of the response motions at Location 7 to the corresponding TRS, we conclude that the switchgear is essentially rigid in the vertical direction. For horizontal vibrations, Figs. 3-6 and 3-8 show that dynamic amplification occurred between 4 and 6 Hz in the side-to-side direction, and between 8 and 11 Hz in the front-to-back direction. Thus we conclude the apparent resonant frequency of the switchgear is about 4 to 6 Hz in the side-to-side, and 8 to 11 Hz in the front-to-back vibration. It suggests that the seismic response of the switchgear is dictated essentially by the ZPA (zero period acceleration) of the vertical base motion, and by the frequency contents of the horizontal base motion within the 4 to 11 Hz range.

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The ZPA of the vertical TRS for all the SSE qualification tests is about 2.5g. For the horizontal component, the envelope of the 3% damping TRS from all the SSE qualification tests is shown in Fig. 3-10 for both the side-to-side and front-to-back directions. The ZPA for the horizontal component of the TRS is also about 2.5g.

It is interesting to note that during the SSE level qualification tests, two additional runs (Runs 14 and 37) were made in which the switchgear was subjected uniaxially to vertical test motions. No chatter of any relays were observed in the two vertical vibration tests. Chatter was usually observed during the bi-directional tests, apparently induced by the horizontal motions, but they did not cause malfunction of the switchgear.

Seismic Capability

To estimate the seismic capability of the subject 4kV switchgear, recall the following structural modifications and mounting conditions that were previously described:

(1) The switchgear was structurally stiffened to a near-rigid configuration for vertical vibrations.

(2) The switchgear was welded at the base and bolted at the top to the supporting structure for both in-plant service and testing conditions.

(3) The overhead potential transformers were removed and qualified separately, to further increase the resonant frequency of the switchgear.

(4) An earthquake joint was inserted at the entry point of the overhead bus ducts into the switchgear, to dynamically decouple the two.

With the above measures implemented, no inadvertent chatter or change of electrical state was observed when the switchgear was subjected to eight bi-directional SSE level dynamic tests (four for side-to-side and vertical, and the remaining four for front-to-back and vertical). All these SSE level tests

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have a TRS with a ZPA of about 2.5g in both the horizontal and vertical directions. As previously discussed, it is apparent from the detailed test data provided in Ref. 4 that the structurally modified switchgear is very rigid such that in the vertical direction it will essentially be sensitive only to the ZPA of the vertical seismic motion at the base of the switchgear. For horizontal vibrations, however, it is not as rigid because its natural frequencies lie in the range of 4 to 11 Hz; consequently, it would be sensitive not only to the ZPA, but to the frequency content of the base motion in this particular frequency range as well. We conclude that the 4kV switchgear, with the structural stiffening modifications and the particular mounting condition implemented, has a minimum seismic capability of 2.5g in ZPA of the vertical base motion. For the horizontal base motion capability, it may be expressed in terms of the 2%, 3% and 5% damping response spectrum shown in Fig. 3-11, which are idealized spectra based on the TRS envelopes with the corresponding damping values (e.g., the 3% damping envelopes in Fig. 3-10). It must be noted that seismic motions at the base of the switchgear having a magnitude comparable to the previously estimated seismic capability could induce chatter in some relays other than the overcurrent relays; however, such chatter would not cause a concern with the required safety function of the switchgear. Furthermore, according to the dynamic test results, such chatter of the relays and switches are essentially induced by the horizontal seismic motions and not by the vertical motion.

It must be pointed out that for standard commercial 4kV switchgear assemblies without any additional structural stiffening, the minimum seismic capability will be lower than that estimated for the particular switchgear we examined. Their minimum seismic capability cannot be reasonably estimated without examining equivalent data similar to that described previously.

Seismic fragility curves for the 4kV switchgear were also derived from our subjective judgment based on the dynamic test data. The subjective judgment is necessarily associated with a large uncertainty because there is no information on the switchgear subjected to levels of test motion above that which we examined. The following assumptions were made to facilitate the estimate of the seismic fragility:

For the purpose of establishing the fragility, the local seismic motion at the switchgear may be sufficiently expressed by one common ZPA for both the vertical and horizontal components of the base motion although, as discussed previously, the horizontal component should rather be represented by a response spectrum. This assumption enables the seismic fragility of the switchgear to be expressed simply as the probability of failure for any given level of ZPA of the switchgear base motion.

(2) The minimum seismic capability, now simply expressed by the 2.5g ZPA, is assumed to be associated with a 5% maximum probability of failure.

(3) The probability distribution of the fragility is lognormal.

With the above assumptions, our judgmental estimate of the median seismic capability and the pertinent variability are as follows:

$\check{A}_H = \check{A}_V =$ median seismic capacity expressed in local ZPA at the switchgear base = 3.9g for both horizontal and vertical directions.

β_u = modeling uncertainty = 0.18

β_r = random variability = 0.09

β = $(\beta_u^2 + \beta_r^2)^{1/2} = 0.20$

The values of β_u and β_r were judgmentally chosen based on the following observations:

(1) The use of the local ZPA at the component base as the parameter for the fragility description for the switchgear incurs a much smaller variability then does the use of either the peak ground acceleration (PGA) or the local spectrum response acceleration at the component base. Use of PGA as the fragility parameter, such as that in Ref. 6, must account for the variability in the ground motion and structure dynamic amplification at the component location in addition to the

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variability in the local ZPA. When using the local spectral response acceleration as the fragility parameter, such as was done by the Seismic Safety Margins Research Program (SSMRP) for the electrical components as derived from the SAFEGUARD Program test data from the U.S. Corps of Engineers (Ref. 6), must one account for the variability in the spectral damping and the shape of the spectrum versus the natural frequencies of the component, which always exceeds the variability in the local base ZPA.

(2) We are dealing with a specific switchgear which has been seismically strengthened and has high seismic capability that is not generic in nature. References 6 and 7 both attempt to predict the fragility for different generic categories of electrical components and therefore the variability associated with that kind of intended application must be necessarily larger.

(3) The ratio of β_u to β_r in Refs. 6 and 7 typically ranged from 1.5 to 2.0. We chose a ratio of 2.0 because the test qualification data for the switchgear led us to the opinion that, as far as the local ZPA is concerned, the random variability would be about one-half of the uncertainty variability only.

The typical value of β_u assumed in Refs. 6 and 7 ranges from 0.35 to 0.50. Based on the above observations, the value of $\beta_u = 0.18$ assumed for the switchgear in question is judged to be consistent with that assumed in Refs. 6 and 7, which use a different parameter for the fragility description. In addition, we are inferring the median seismic capacity of the switchgear through extrapolation of the maximum test qualification acceleration data. The extrapolation was done with conservatism in mind because the seismically upgraded switchgear already has a high seismic capability (as required by the plant design), for which purpose a smaller variability will be consistent.

Based on the previous reasoning, the same value of β_u and β_r will be used to describe the fragility of the four electrical components considered in the following discussion.

3.3 Safeguard Relay Boards

Description of Equipment

The safeguard relay boards are standard commercial items. They are steel cabinets 94 inches high, 43 inches wide and 34 inches deep. Each one weighs about 1,500 pounds. An array of electrical relays, switches and lights are mounted in a semi-flush manner on the steel cabinets. Doors at the back of the cabinets provide access to the wiring and secondary devices such as fuses, test and cut-out switches, and a timing relay.

Of the six boards installed in the Diablo Canyon Nuclear Plant, five are identical to one another. They are Safeguard Relay Boards F, G and H of Unit 1 and G and H of Unit 2. Safeguard Relay Board F of Unit 2 has the same physical outline but does not contain the diesel generator protective relays that are contained in the other five boards because there are only five diesel generators at Diablo Canyon.

Safeguard Relay Board H of Diablo Canyon Unit 2 was selected for testing to qualify all Safeguard Relay Boards. Figs. 3-12 and 3-13 show the front and side views of the test setup for the Safeguard Relay Board H (reproduced from Ref. 3). Table 3-1 lists the relays on the Board H (reproduced from Ref. 3). In this device table, the "Device Number" is the PG&E designation of the relay, "Type" is the manufacturer's designation, "Use" indicates the function of the device in the plant electrical system, and "Affect Class 1E Function" is shown with yes or no as appropriate.

The relay board was bolted to the seismic shaking table with eight 1/2" x 13" bolts, to simulate the rigid in-plant floor mounting condition.

Safety Function

The devices on the safeguard relay boards are required to perform the following safety functions in the plant:[3]

(a) Initiate start of diesel generators in case of loss of the off-site stand-by power source and loss of the 4kV bus voltage.

(b) Upon loss of 4kV bus voltage, initiate transfer of the 4kV bus from the station auxiliary transformer to the stand-by start-up transformer and, if necessary, to the diesel generators.

(c) Stop the diesel generator and trip its output breaker on sensing differential phase current.

(d) Initiate start of the component cooling water pump on cooling water low pressure.

Seismic Failure Modes

As for the 4kV switchgear examined previously, structural failure during seismic events is not the governing failure mode for the boards. Functional failure due to inadvertent change of the electrical state or chattering in the control devices (e.g., relays, timer) is the prevailing seismic failure mode. According to Ref. 3, the possible functional failure modes of the safeguard relay boards are as follows:

(1) Inadvertent operation of the Diesel Generator Differential Relay (Device 87HHG in Table 3-1), preventing the diesel generator from tripping and the 4kV diesel generator breaker from opening upon the diesel generator differential current flow.

(2) Inadvertent chattering (closing) of the normally open contacts of the Auxiliary Relays (Devices 32XHH7, 32YHH7, 87XHHG, 87YHHG, 40XHH7 and 40YHH7). Such spurious closure of the contacts could seal in the respective auxiliary relay, causing the diesel generator breaker to open and, in the case of the 87XHHG and 87YHHG relay, causing the diesel generator itself to trip. The 87X and 87Y relays must remain operational during and after a seismic event.

(3) Inadvertent change of electrical state in the Transfer, Interlocking, and Trip Relays (Devices 4HH, 3HH1 and 5HH13, respectively). These must remain functional during and after a seismic event.

(4) Malfunctioning of the 4kV switchgear Bus Undervoltage Auxiliary Relay (Device 27ZHHB2) upon contact closure of the 27HHB2 bus undervoltage relay during and after a seismic event.

(5) Malfunctioning of the Diesel Auto Transfer Timer (Device 62HH2) upon demand during a seismic event.

Modifications to Improve Seismic Performance

The unit tested is a standard commercial item; no special modifications were made to improve seismic performance. The rigid in-plant mounting condition was, however, simulated during testing.

Seismic Qualification

The Safeguard Relay Board H has been subjected to extensive dynamic tests. They include uniaxial frequency sweep tests having a ZPA of 0.2g, OBE level biaxial qualification tests, and SSE level biaxial qualification tests. In each biaxial test, one horizontal (either side-to-side or front-to back) and one vertical test motion were simultaneously simulated on the shaking table. The horizontal test motion is typically a multi-frequency random motion. The vertical test motion is typically a multi-frequency random motion superimposed with a sine best motion having the specified frequency. The qualification tests conformed to the requirements of the IEEE Standard 344-1975 and the USNRC Regulatory Guide 1.100.

The test setup for the relay board is shown previously in Figures 3-12 and 3-13. To simulate the rigid floor mounting condition in the plants, the relay board was bolted at its base to the shaking table with eight 1/2" x 13" bolts. In addition, one relay was rigidly mounted directly onto the shaking table for the purpose of independent evaluations.

72

Besides monitoring the test motions at the shake table, the response accelerations at three locations on the relay board, at the cabinet front, and at the rigidly mounted relay were monitored. Figure 3-14(a) illustrates the three locations, 1, 2 and 3, on the relay board where accelerometers were attached. To monitor the structural performance of the relay board cabinet, two strain gauges were installed on the lateral structural members inside the relay board, at 7" above the floor, as shown in Fig. 3-14(b). Functionality of the relay board was monitored through the test setup wiring beyond the termination points.

To qualify for the SSE criteria for the Hosgri design earthquake, seven biaxial tests were done for the front-to-back and vertical directions (Runs 9 to 15), and five for the side-to-side and vertical directions (Runs 23 to 27). As an example, Fig. 3-15 compares the 3% damping front-to-back TRS with the corresponding 3% damping spectrum of the response motion at Location 1 from Run 14. Similarly, Fig. 3-16 compares the 3% damping vertical TRS with the corresponding spectrum of the vertical response motion at Location 1 on the relay board, from the same run. For the side-to-side and vertical tests, the 3% damping TRS and the Location 1 response spectrum from Run No. 27 are compared in Figs. 3-17 and 3-18 for the side-to-side and vertical components, respectively. Figs. 3-15 to 3-18 clearly show that the safeguard relay board is essentially rigid in the vertical direction, the apparent resonance frequency exceeding 33 Hz. For both the front-to-back and side-to-side horizontal directions, the resonance frequency appears to be about the same, being between 12 and 15 Hz, although the dynamic amplification in the front-to-back direction is much larger. Comparing the safeguard relay board with the 4kV switchgear, both are rigid in the vertical direction but not in the horizontal direction. On the basis of the apparent resonance frequency, the safeguard relay board is dynamically stiffer than the 4kV switchgear in both horizontal directions.

Based on the test results such as the ones shown in Figs. 3-15 to 3-18, we conclude that in the vertical direction the safeguard relay board essentially will be sensitive to only the ZPA of the seismic motion at its base. In the horizontal direction, the relay board will be sensitive to the frequency content in the base motion above 12 Hz. The degree of sensitivity will be larger for the front-to-back than for the side-to-side direction because the test data show a larger dynamic amplification in the front-to-back direction. The envelopes of the 3% damping horizontal TRS are shown in Fig. 3-19.

According to Ref. 3, the evaluation of the strain gauge traces showed that the structural members of the relay board were stressed during the tests well within their design limits. No physical damage to the relay board or its devices was observed, either. This substantiated the previous statement that the structural failure would not be a governing failure mode for the relay board. Regarding the test results about the functionality performance of the safeguard relay board, Ref. 3 shows that anomalies occurred for relays 27XZHHB2, 32XHH7, and 40XHH7 only. Evaluations of the anomalies, according to Ref. 2, are summarized as follows:

(1) Pulsation of the 27ZHHB2 relay (4kV Bus Undervoltage Auxiliary Relay) during the testing was caused by the chatter of the deenergized 27HBB2 relay. Testing performed on the 4kV switchgear, as previously discussed, has demonstrated that pulsation of the 27ZHHB2 relay would not compromise the safety function of power transfer of the 4kV bus from the station auxiliary transformer to the stand-by start-up transformer and, if necessary, to the diesel generators.

(2) The 32XHH7 and 40XHH7 auxiliary relays experienced momentary change of state of the contacts during a portion of the tests. The pulsation of these relays were due to chatter of the prime relays (Reverse Power Relay and Loss of Field Relay) because the anomaly did not occur when the cut-out switches for the prime relays had been opened. During plant operations these relays are normally cut out and hence the anomaly would not occur in a seismic event.

The results demonstrated that, for the qualification tests having a horizontal ZPA of 2.7g and vertical ZPA of 3.4g at the base of the relay board, pulsation of the 4kV Bus Undervoltage Auxiliary Relay and two other auxiliary relays occurred but did not cause a malfunction.

Seismic Capability

According to the test results discussed previously, we estimated the minimum seismic capability of the safeguard relay board as follows:

$(A_V)_{min}$ - A base motion ZPA equal to 3.4g because the relay board is rigid in the vertical direction

$(A_H)_{min}$ - A response spectrum having a ZPA of 2.7g for the base motion because the relay board is not rigid in the horizontal direction, the resonance frequency being between 12 to 15 Hz. The minimum capability response spectrum for 3% damping is shown in Fig. 3-20. It is an idealized version of the TRS envelope for the horizontal direction as shown in Fig. 3-19. At this level of seismic excitation, some auxiliary relays could chatter but would not comprise the safety function of the safeguard relay board.

To estimate the fragility of the safeguard relay board, we used the same assumptions previously adopted for the 4kV switchgear and potential transformer, namely:

(1) The base motions for the relay board may be sufficiently expressed by their ZPAs.

(2) The minimum seismic capability, expressed by the ZPA, is associated with a maximum failure probability of 5%.

(3) The probability distribution of the fragility is lognormal.

Consistent with these assumptions, our estimate of the median seismic capability and the pertinent variability are as follows:

$\check{A}_H$ = 4.2g (horizontal base motion ZPA)

$\check{A}_V$ = 5.3g (vertical base motion ZPA)

$\beta_u = 0.18$

$\beta_r = 0.09$

where β_r and β_u are based on the assumptions discussed in Section 3.2.

3.4 Potential Transformer

Description of Equipment

The 4160/120V potential transformers are standard commercial items. They are housed in a metal cabinet 26 inches wide, 22 inches high and 35.5 inches deep. The butyl-molded transformer is fastened to a roll-out slide which can be pulled forward together with the cabinet front. Contact fingers mounted to the stationary housing provide the electrical connections to the primary and secondary windings of the slide mounted transformers. The transformers are usually mounted on top of the 4kV switchgear of which they are an electrical accessory. The transformers discussed here were removed from the top of the switchgear during the qualification tests of the switchgear, as mentioned previously (Figs. 3-1 and 3-2). They are instead mounted on a rigid stand and fastened to the floor near the switchgear in the plant. The transformers were thus qualified separately from the switchgear.

Safety Function

The safety function of the transformer is to provide a signal for control and instrumentation, proportional to the level of high voltage of the bus or feeder to which the transformer is connected. The signal must be provided at all times without interruption.

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Seismic Failure Modes

The transformer itself has no moving parts that could compromise its required safety function. Structural integrity, by inspection, would not be a potential failure mode provided that the transformer is rigidly bolted to the floor as was done during the qualification tests. The only possible seismic failure mode is interruption of the voltage signal caused by the malfunction of the primary and secondary contact fingers.

Modifications to Improve Seismic Performance

The unit tested is a standard commercial item; no special modifications were made to improve seismic performance. The rigid in-plant mounting condition was, however, simulated during testing.

Seismic Qualification

The transformer was seismically qualified for the SSE by dynamic tests, the intent of which was to demonstrate the integrity of the contact fingers. The transformer was tested along side the safeguard relay board (see Fig. 3-12); the test sequence was the same as that described previously for the safeguard relay board.

The test setup and the test motions conformed to the IEEE Standard 344-1975 requirements. The transformer cabinet was rigidly bolted to a steel plate which in turn was welded to the shake table. This rigid mounting condition simulates the in-plant service condition. Two primary and two secondary contact finger assemblies were connected in series and wired to direct readout recorder for monitoring their functionality during the dynamic tests.

Because the transformer was tested concurrently with the safeguard relay board, the TRS's are the same as those for the relay board. The horizontal TRS envelope is shown in Fig. 3-19, having a ZPA of 2.7g. The ZPA of the vertical TRS is 3.4g, as discussed previously for the relay board qualification tests. No information is available on the dynamic response motion of the potential transformer.

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The test results indicate that chatter of the contact fingers did not occur at all during the tests. Physical damage was not observed either.

Seismic Capability

In view of the test results, we judged that the minimum seismic capability of the transformer can be sufficiently represented by the ZPA of the base motions in both the vertical and horizontal direction. We assumed this to be the case even though response information of the transformer during the tests is not available. Thus, we have:

$$(A_H)_{min} = 2.7g$$

$$(A_V)_{min} = 3.4g$$

For the fragility, we estimated the median seismic capacity of the transformer based on the same assumptions previously applied to the 4kV switchgear. This is, the minimum ZPA capability corresponds to a 5% maximum probability of failure associated with a 95% confidence level, and the uncertainty and random variability are 0.18 and 0.09, respectively. Thus our estimate for the fragility of the transformer, in terms of the base motion ZPA, is

$$\check{A}_H = 4.2g$$

$$\check{A}_V = 5.3g$$

$$\beta_u = 0.18$$

$$\beta_r = 0.09$$

Note that the transformer was initially placed on top of the 4kV switchgears during the early stage of the SSE qualification tests for the switchgears, before it was removed to improve switchgear seismic performance (see Section

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3.2). During these early tests, the transformer experienced a ZPA of 4g to 5g (the motion at the top of the switchgear cabinet) without experiencing any apparent anomaly. This encouraging result is consistent with our estimate of the median seismic capacity of the transformer, giving us confidence that the assumptions we used for the fragility estimate are reasonable.

3.5 Emergency Light Battery Pack

Description of Equipment

The Emergency Light Battery Pack (Fig. 3-13) is a standard commercial metal chassis 8-hour rated nickel-cadium battery with a battery charger and two 6 VDC sealed beam lights. It was qualified with essentially the same TRS as for the 4kv switchgear, safeguard relay boards, and potential transformers because they all are located at the same floor elevation in the turbine building.

Safety Function

The Emergency Light Battery Pack is required to provide eight hours of lighting if the redundant normal AC, Emergency AC and 125 VDC lights are lost due to seismic or fire in designated Class 1E operating areas. The unit must satisfy the following requirements in order that it perform its safety function during and after a seismic event.

(1) Upon loss of emergency AC power the unit will automatically revert to battery power and light the sealed beam lights.

(2) Upon return of AC power the unit lights will turn off and its charger will recharge the battery at the high charge rate, equalizing charge rate, or the trickle charge rate.

(3) After a seismic event the unit will power the sealed beam lights for eight hours.

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(4) The battery charger will recharge the battery in twelve hours.

The unit was required to demonstrate the above functions during and after the tests.

Seismic Failure Modes

With the implementation of structural modification to the mounting, structural damage is no longer a governing failure mode. The potential failure modes are:

(1) Electrolyte leakage, which will be indicated by external moisture or change in electrolyte level.

(2) Malfunction of the lights in the unit, upon either deenergization or reenergization of the 120 VAC to the unit.

(3) Disruption of the 8-hour continuous power supply to the sealed beam lights, when required, after the seismic event and upon deenergization of the 120 VAC.

(4) Failure to recharge the unit within the 12-hour recharge cycle upon reenergization of the 120 VAC and subsequent to the 8-hour continuous power supply to the sealed beam lights.

Modifications to Improve Seismic Performance

A structural modification was made to the mounting to increase the rigidity of the equipment. The modification consisted of two 1/2" x 1" steel straps placed across the top of the battery, which are in turn are bolted to the mounting shelf using 1/4" threaded rod with standard nuts and washers. The in-plant mounting of the battery pack utilizes this structural modification.

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Seismic Qualification

The unit was tested 13 times for the SSE level qualification in addition to 10 runs for the OBE level. As previously mentioned, the unit was mounted with the same structural modification as that implemented in the plant. The TRS for the SSE level test in essentially the same as that for the safeguard relay boards and potential transformers (see Fig. 3-19 for the horizontal TRS envelopes). The unit performed the required safety functions during and after the tests, with no structural damage being observed.

Seismic Capability

As for the potential transformers, no information is available regarding the resonance frequency of the battery pack. We therefore assume that the minimum seismic capability of the battery pack can be adequately represented by the ZPA of the base motion for both the horizontal and vertical directions, provided that the mounting condition conforms to the one adopted for Diablo Canyon. Therefore,

$$(A_H)_{min} = 2.7g$$
$$(A_V)_{min} = 3.4g.$$

The estimate for the fragility of the battery pack follows that for the safeguard relay board and the potential transformers. Thus, we have

$$\check{A}_H = 4.2g$$
$$\check{A}_V = 5.3g$$
$$\beta_u = 0.18.$$
$$\beta_r = 0.09$$

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3.6 Station Battery and Racks

Description of Equipment

Each of the Diablo Canyon Units 1 and 2 has three identical standard commercial batteries composed of 60 cells installed in battery racks at the 115' elevation in the Auxiliary Building. In order to withstand the design seismic loads, the battery racks have been braced such that the natural frequency exceed 33 Hz (see Fig. 3-2).

The average operating current on a typical Diablo Canyon battery bus is about 100 amperes. In actual operation this current is supplied by the battery charger, with the battery floating on the charger and connected to the bus. Should the battery charger trip, the battery would supply the 100 amperes.

Safety Function

The Station Batteries must provide nominal 125 VDC power to supply the station DC loads in the event that the AC source to one or more battery charger becomes unavailable. To accomplish this safety function, the Station Batteries must be capable of satisfying the following performance criteria during and after a seismic event:

(1) The cells shall provide continuous current output at a steady voltage.

(2) The battery cells shall not be structurally damaged.

(3) The battery shall be able to accept charging current when required.

(4) After a seismic event, the battery shall meet its 8-hour discharge requirement in accordance with IEEE Standard 450-1975.

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Seismic Failure Modes

In its standard commercial configuration, the battery and rack could be susceptible to structural damage and possible leakage of electrolyte when subjected to seismic motions having sufficient intensity. Seismic motions could also cause malfunctions of the battery and rack including:

(1) Fluctuation in the output current voltage.

(2) Incapacity to accept charging current or meet the 8-hour discharge requirement after a seismic event.

Modifications to Improve Seismic Performance

The structural rigidity of the battery and rack has been increased through the addition of diagonal braces and side-rail shims. These measures, plus rigid floor mounting, represent the actual in-plant mounting condition. The battery cells are held in the rack by the standard bolt and straps supplied by the manufacturer.

Seismic Qualification

During qualification testing two battery cells were mounted in a rigid fixture to simulate their service mounting condition (see Fig. 3-21). The rigid mounting condition was achieved by adding diagonal braces and side rail shims. The two batteries were connected in series to a one-ohm load, and the standard battery straps and bolts and nuts provided with the 60-cell battery were used in the test setup. The current and voltage of both cells were monitored before, during and after the seismic tests.

The test motions are the typical biaxial, multi-frequency random motions which conformed to the IEEE Standard 344-1975 requirements. The ZPA of the horizontal test motion is about 2.5g, and the corresponding vertical ZPA is about 1.1g. According to Ref. 1, the resonance frequency of the racks exceeds 33 Hz and the racks may be considered rigid. A seismic structural analysis has been performed for the racks to confirm its structural integrity when subjected to the SSE design seismic loads. Thus,

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$$(A_H)_{min} = 2.5g$$

$$(A_V)_{min} = 1.1g$$

With assumptions consistent with those previously adopted for the other components, our estimate for the seismic fragility of the station battery and racks including the structural bracing enhancement are as follows.

$$\check{A}_H = 3.9g$$

$$\check{A}_V = 1.7g$$

$$\beta_u = 0.18$$

$$\beta_r = 0.09$$

3.7 Discussion of Results

To demonstrate how "high-level" qualification testing can be used to assess ultimate seismic capacity, we assessed in detail five components subjected to actual tests as part of the Hosgri seismic evaluation performed by the Pacific Gas & Electric Company. In our assessment we examined the seismic qualification test results for the Diablo Canyon 4kV switchgear, potential transformer, safeguard relay board, emergency light battery pack, and station battery and racks. For each component, we presented a brief description of the component, mounting condition, structural modifications (if any), safety functions, potential seismic failure modes, and qualification test methods and results. Based on the test methods and results, we empirically established the minimum seismic capacity as being equal to the highest seismic level to which it was subjected during the qualification tests. The minimum seismic capabilities are represented by the ZPA of the local base motion although we also recognize that if the component is "flexible", that is, having an observed resonance frequency lower than 33 Hz, spectral acceleration may be a more "appropriate" response parameter on which to base a fragility description.

We then assumed the ZPA associated with the estimated minimum seismic capability represents the high-confidence, low probability of failure ("HCLPF") seismic capacity, which corresponds to a 5% maximum failure probability at a 95% confidence level. We further assumed the random and uncertain variabilities to be $\beta_r = 0.09$ and $\beta_u = 0.18$, respectively. Based on these assumptions, the median seismic ZPA capacities were inferred.

Table 3-2 presents an overall summary of the seismic fragilities of the five electrical components we examined. The corresponding seismic fragility curves and HCLPF capacities are presented in Figs. 3-22 to 3-24. The HCLPF seismic capability for all five components exceeds 2.0g, except that for the station batteries and racks it is 1.1g for the vertical direction.

The empirically estimated HCLPF seismic capability and seismic fragility may be used as a screening basis when evaluating the same or similar electrical components installed at other plants, provided they incorporate the similar structural modifications and mounting conditions listed in Table 3-2. A reduced seismic fragility must be used if such modifications are not implemented.

From the results of our assessment we make the following general observations:

- in principle, a "HCLPF" approach can be used to infer ultimate capacity provided that sufficient information is available from which to estimate how various factors affect seismic performance. These factors include not only specific hardware modifications made to enhance seismic performance, but also how the component is mounted.

- based on our evaluation, each of these items in its as-qualified configuration would rate as a "high capacity" component according to our prioritization guidelines (see Section 2). Note that the "as-qualified" configuration includes the rigid mounting condition applied for all components in addition modifications, if any, in the component itself.

- all of the components considered in this evaluation were standard commercial items (before modifications, if any), suggesting a high degree of commonality with similar equipment installed in other plants. This result is encouraging because it suggests commonality among certain "standard" equipment items and therefore that high-level test results can be used to substantiate "high" seismic capacity levels assigned to like equipment at plants having lower SSE requirements.

- with one exception, all components were qualified in their standard commercial configurations with no or only relatively minor modifications. This result suggests that the seismic capacity of like equipment in other plants could be substantially improved, if necessary, through similar modifications. Note for each component that particularly reliance was placed on rigid mounting conditions.

- a detailed evaluation of high-level data can suggest component modifications that may significantly increase seismic capacity, or areas of emphasis in seismic margins reviews.

However, a "bottom-up" assessment of seismic capacity (i.e., fragility level estimated from HCLPF capacity) as applied in this evaluation suggests that fragility level increases with uncertainty, which is clearly non-conservative. Consequently, extreme care must be exercised in selecting the uncertainty parameters used to infer the "fragility level" of a component. Unfortunately, the information necessary to select these parameters is often not available from existing data, in which case the HCLPF-derived fragility descriptions have a high degree of inherent uncertainty. For certain high-capacity components, this uncertainty may be tolerable if only a "lower bound" fragility (a HCLPF capacity, for example, or a 95% fragility curve) is needed for regulatory decision-making or is adequate for PRA applications. This may be true, for example, for the Diablo Canyon components considered in this assessment. In general, however, this uncertainty implies that a "top-down" approach -- estimating HCLPF capacities from measured fragility levels -- is

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still preferable to assessing seismic performance when a detailed fragility description is desired, particularly for low-capacity equipment.

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Table 3-1

Safeguard Relay Board "H" Device Table

Device	Type	Use	Affect Class 1E Function	Remarks
25HH	IJS	Synchronism Check	no	Used during tests only
32HH7	CRN-1	Reverse Power	no	Used during test only
46HH7	COQ	Negative Sequence	no	Alarm only
59HHU	SV	Start-up Voltage	no	Chatter will not produce abnormal operation
27HHU	CV-2	Start-up Under Voltage	no	Chatter could start diesel. This is failsafe
62HH1	TD-5	Start-up Auto Transf. Timer	no	Chatter will not produce abnormal operation
87HHG	SA-1	Diesel Gen. Differential	yes	Monitor Aux. Relays
40HH7	KLF	Loss of Field	no	Used during tests only
32XHH7	AR	Rev. Pwr. Auxiliary	yes	Monitor NO contact
32YHH7	AR	Rev. Pwr. Auxiliary	yes	of 32YHH7
87XHHG	AR	Diesel Gen. Diff.	yes	Monitor NO contact
87YHHG	AR	Auxiliary Relays	yes	of 87YHHG
40XHH7	AR	Loss of Field	yes	Monitor NO contact
40YHH7	AR	Auxiliary Relays	yes	of 40YHH7
4HH	LORE	Diesel Gen. Auto Transf. Control Relay	yes	See 3HH1
3HH1	LORE	Diesel Gen Auto Transf. Interlocking Relay	yes	Monitor 1NO & 1NC cont. (typ. for 4HH & 5HH13)
5HH13	LORE	St-up Auto Transf. Trip Relay	yes	See 3HH1
PS190XH	SG	Comp. Cool Wtr. Low	no	Chatter would start
PS191XH	SG	Press. Aux. Relay		Comp. Cool. Wtr. Pp. This is failsafe
27XHHB2	SG	Bus UV Aux. Relay (st.-up & 4kV Bus)	no	Chatter would start diesel. This is failsafe.
25XHH	SG	Synch. Check Aux. Rel.	no	Used during test only

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Table 3-1 (cont.)

Safeguard Relay Board "H" Device Table

Device	Type	Use	Affect Class 1E Function	Remarks
4HH7	SG	Diesel Gen. Auto Transf. Close Relay	no	Chatter will not produce abnormal operation
27HHDC	SG	DC Contr. Bus UV Rel.	no	Alarm only
27GHDC	SG	DC Contr. Bus UV Rel.	no	Alarm only
27ZHHB2	SG	4kV Bus UV Aux. Rel.	yes	Connect NO Cont. to 5HH13 and monitor trip
27YHHB2	SG	Same as 27XHHB2	no	Same as 27XHHB2
4HH14X	SG	Start-up Auto Transfer	no	Chatter will not produce
4HH14	SG	Close Aux. Relays	no	abnormal operation
62HH2	AGASTAT	Diesel Auto Transfer Timer	no	Chatter will not produce abnormal operation

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Table 3-2

Seismic Fragility Expressed in Local Base ZPA

Component	$\check{A}_h$	$\check{A}_v$	β_u	β_r	Modifications
4.16KV Switchgear	3.9g	3.9g	0.18	0.09	· Addition of stiffener plates; · Removal of P.T. from top; · Insertion of seismic flexible joint at entry of overhead bus duct; · Rigid mounting at top & base.
Potential Transformer	4.2g	5.3g	0.18	0.09	· Standard commercial device; · Rigid base mounting.
Safeguard Relay Board	4.2g	5.3g	0.18	0.09	· Standard commercial device; · Rigid base mounting.
Emergency Light Battery Pack	4.2g	5.3g	0.18	0.09	· Addition of steel straps across battery tops, and straps bolted to mounting shelf with standard fasteners.
B.O.P. Station Batteries/Racks	3.9g	1.7g	0.18	0.09	· Standard commercial batteries; · Addition of bracings and side rail shims to battery rack.

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Fig. 3-1. 4160-volt switchgear on test stand prior to removal of potential transformers.

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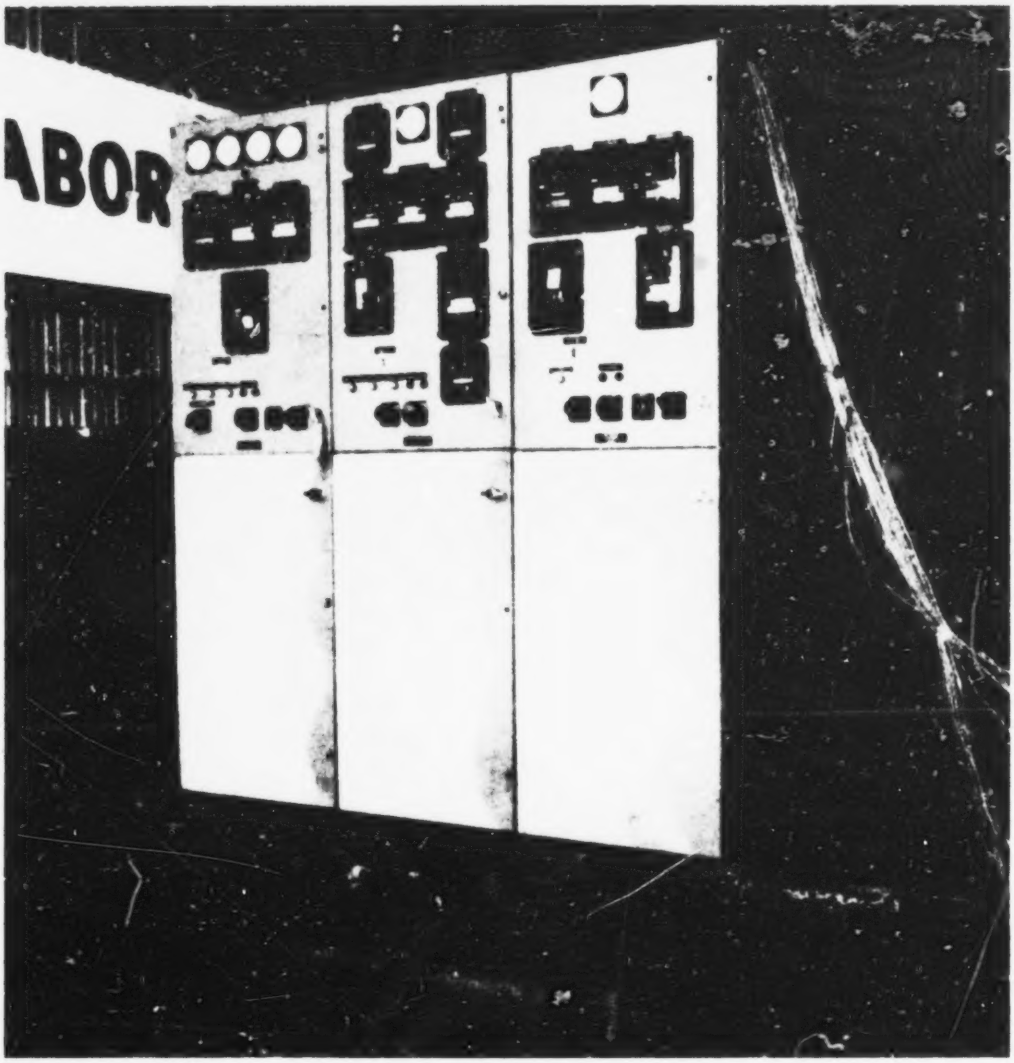

Fig. 3-2. 4160-volt switchgear on test stand after removal of potential transformers.

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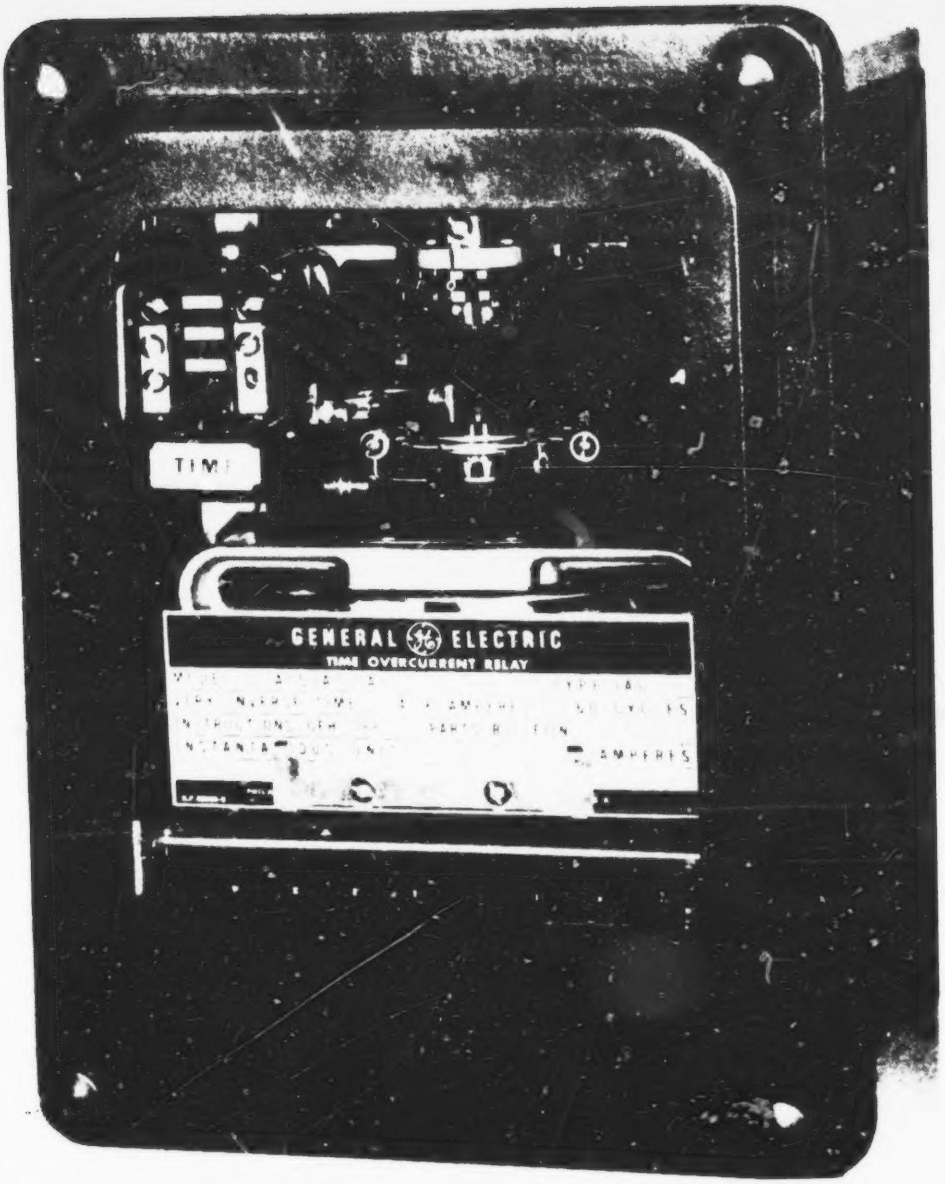
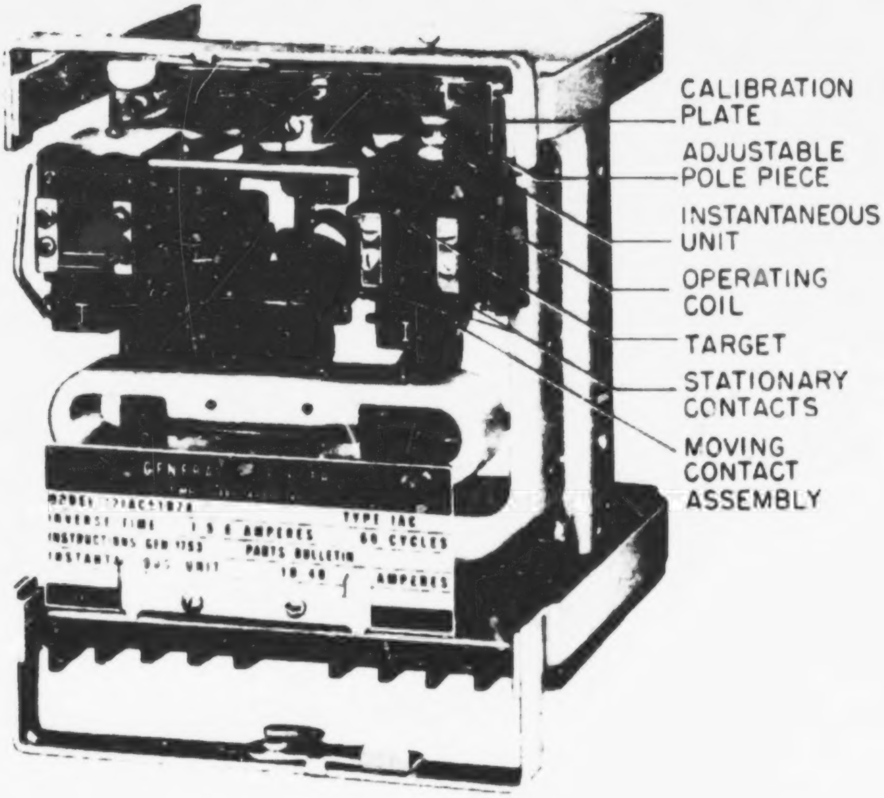

TIME
GENERAL ELECTRIC
TIME OVERCURRENT RELAY
AMPERES
CYCLES
AMPERES

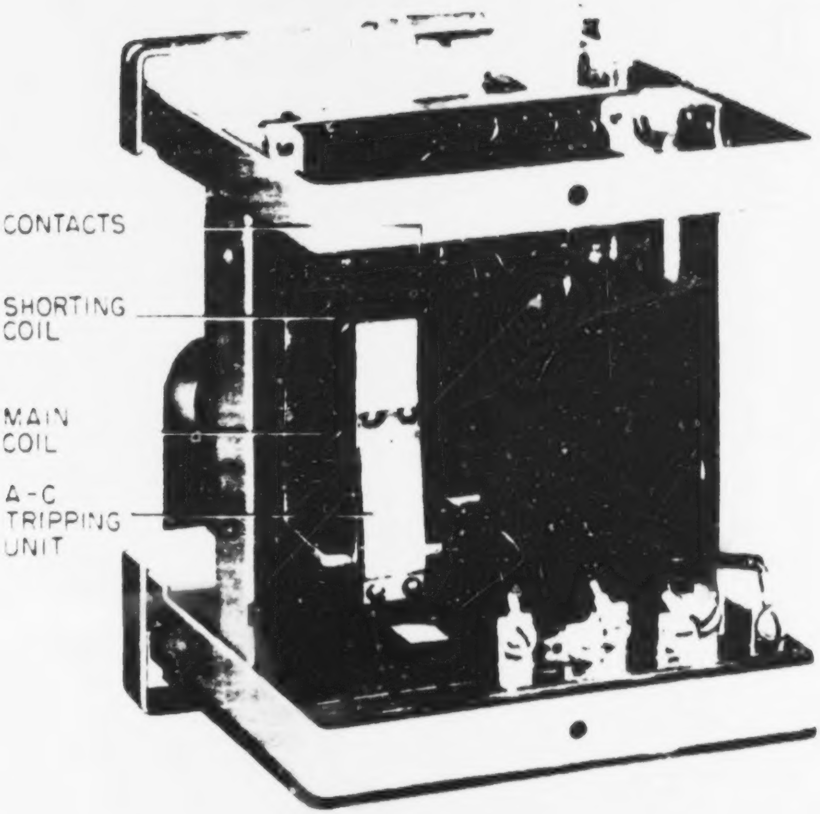
Fig. 3-3. Typical overcurrent relay.



CALIBRATION PLATE
ADJUSTABLE POLE PIECE
INSTANTANEOUS UNIT
OPERATING COIL
TARGET
STATIONARY CONTACTS
MOVING CONTACT ASSEMBLY
GENERAL ELECTRIC
INVERSE TIME
AMPERES
TYPE IAC
PARTS BULLETIN
60 CYCLES
AMPERES

(a) Front view

Fig. 3-4. Induction unit for typical overcurrent relay.


CONTACTS
SHORTING COIL
MAIN COIL
A-C TRIPPING UNIT

(b) Rear view

Fig. 3-4 (cont.). Induction unit for typical overcurrent relay.

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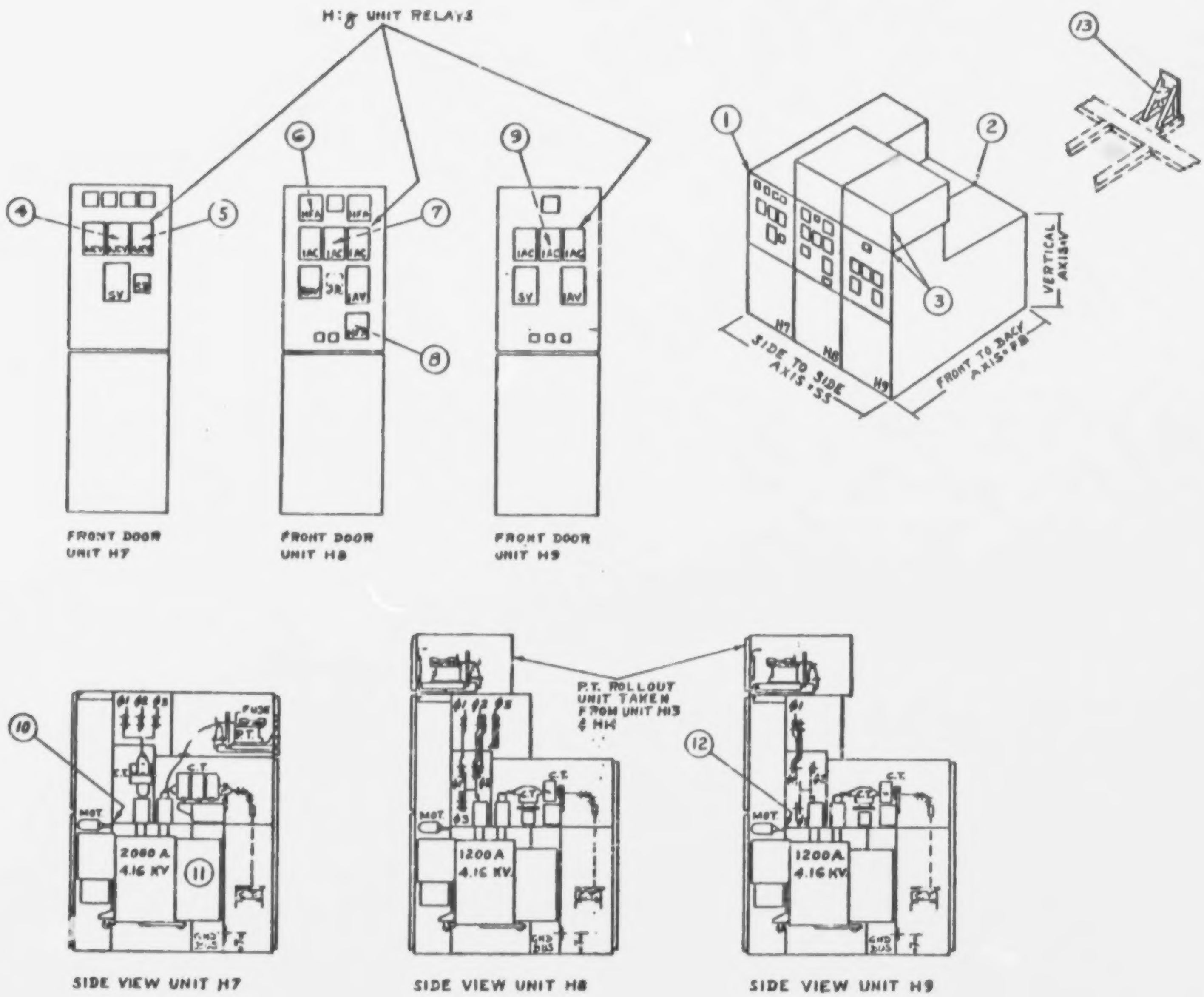
H:8 UNIT RELAYS
①
②
③
④
⑤
⑥
⑦
⑧
⑨
⑩
⑪
⑫
⑬
HFA
IAC
SV
IAV
H7
H8
H9
SIDE TO SIDE AXIS • SS
FRONT TO BACK AXIS • FB
VERTICAL AXIS • V
FRONT DOOR UNIT H7
FRONT DOOR UNIT H8
FRONT DOOR UNIT H9
P.T. ROLLOUT UNIT TAKEN FROM UNIT H13 & H14
φ1 φ2 φ3
FUSE
P.T.
C.T.
MOT.
2000 A 4.16 KV
1200A 4.16 KV
GND BUS
SIDE VIEW UNIT H7
SIDE VIEW UNIT H8
SIDE VIEW UNIT H9

Fig. 3-5. Locations of accelerometers for monitoring switchgear response motions.

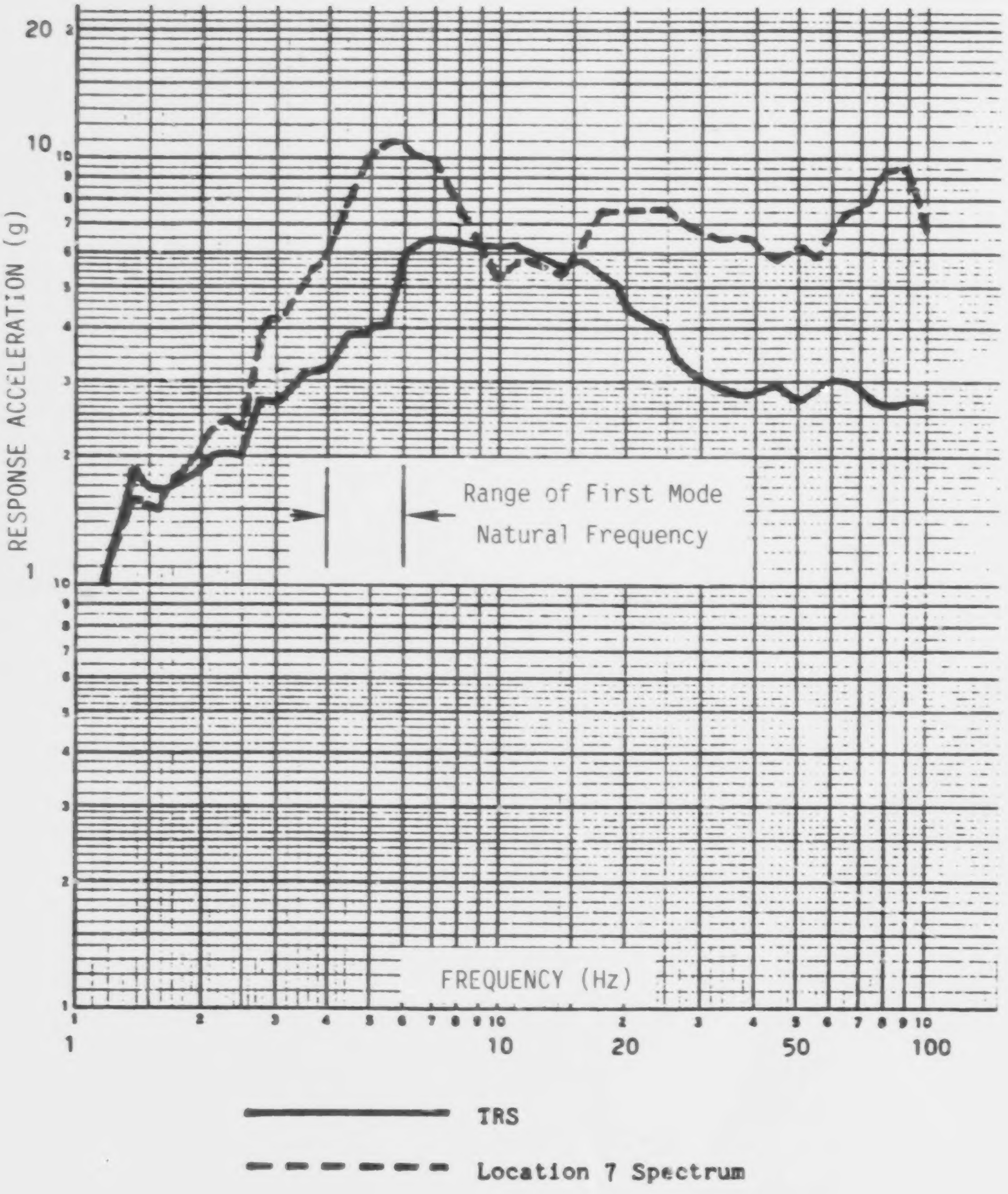

Fig. 3-6. Input motion TRS and response spectrum at switchgear Location 7 during Run 16, S-S direction (5% damping).

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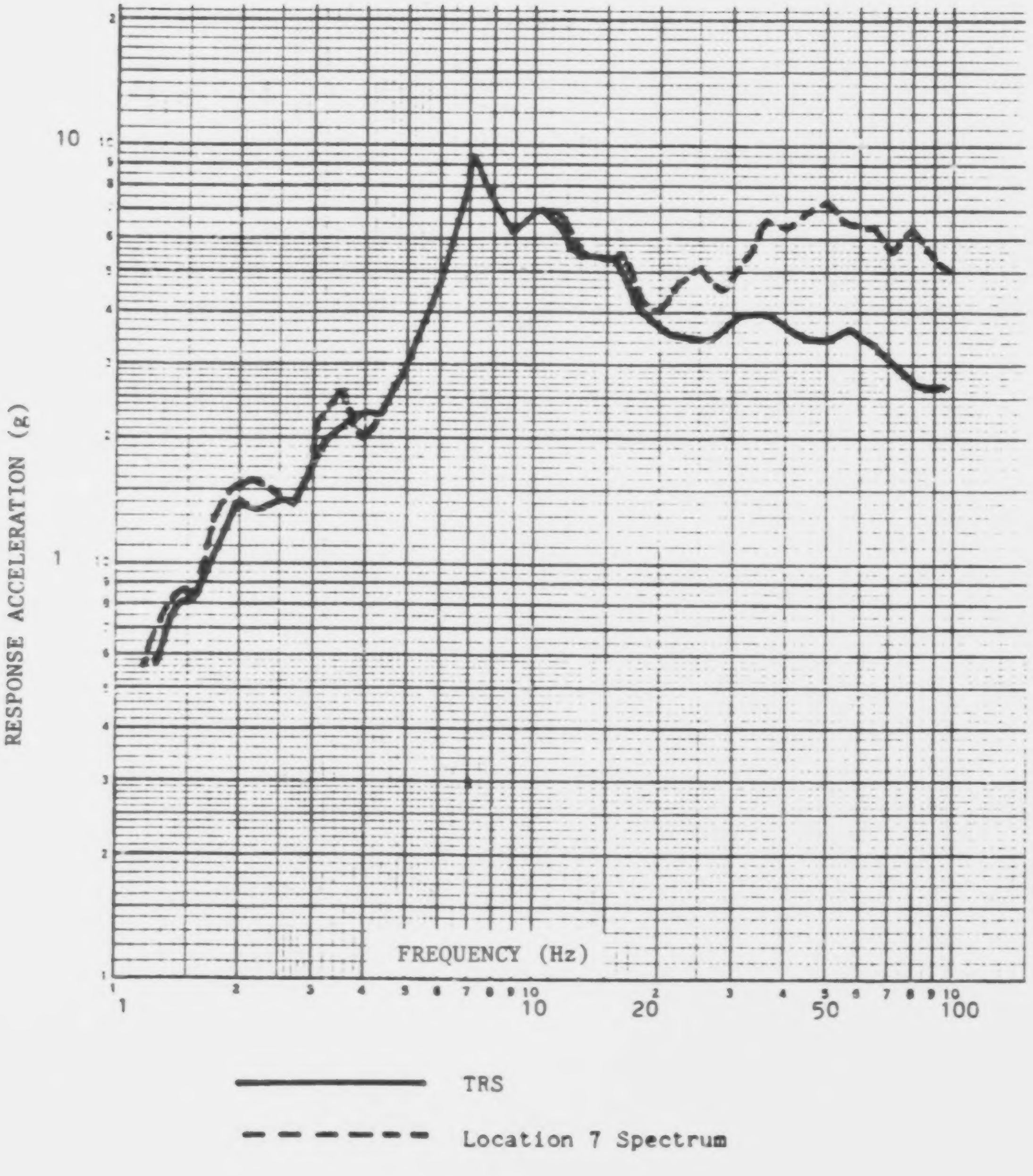

Fig. 3-7. Input motion TRS and response spectrum at switchgear Location 7 during Run 16, vertical direction (5% damping).

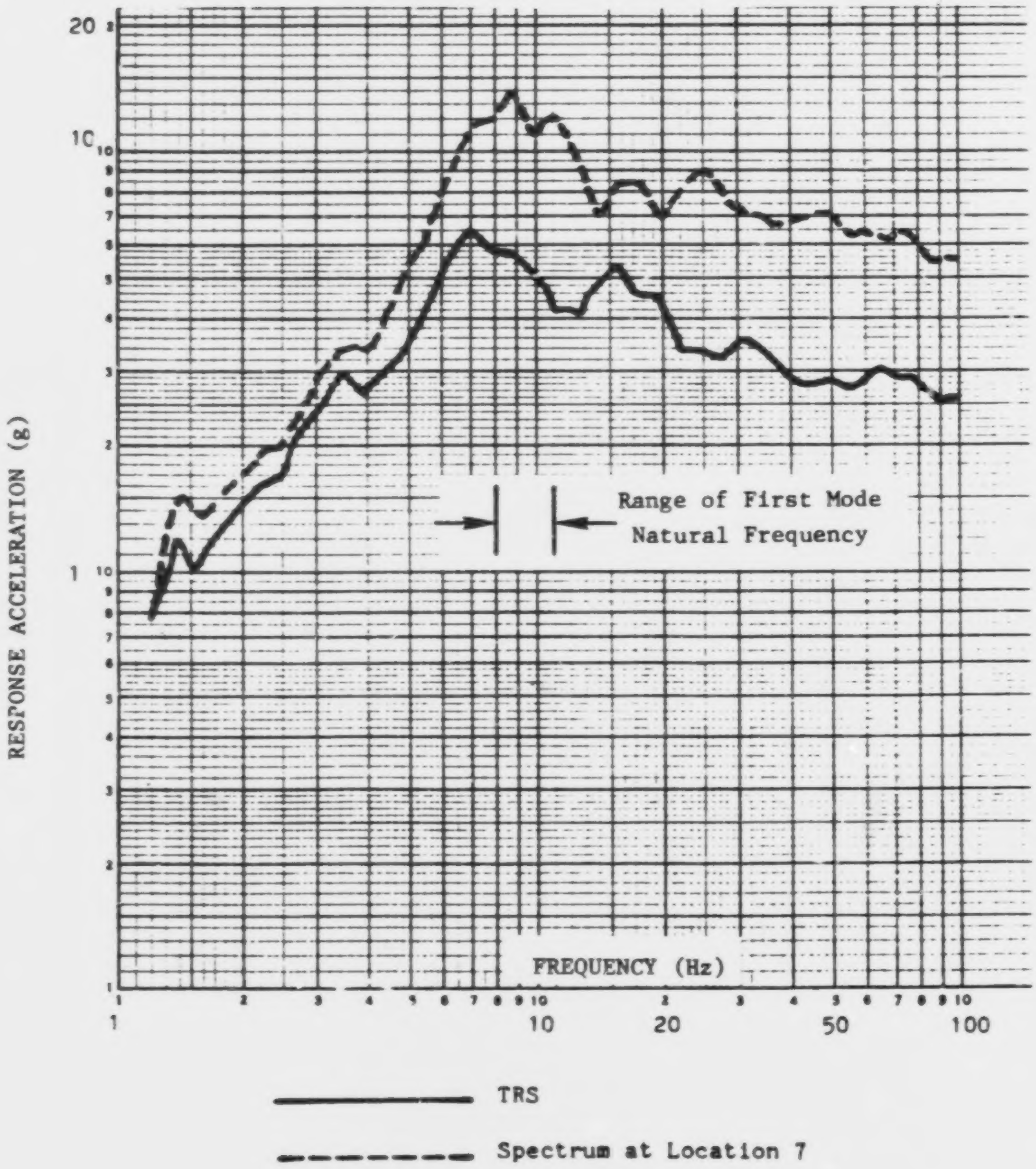

Fig. 3-8. Input motion TRS and response spectrum at switchgear Location 7 during Run 31, F-B direction (5% damping).

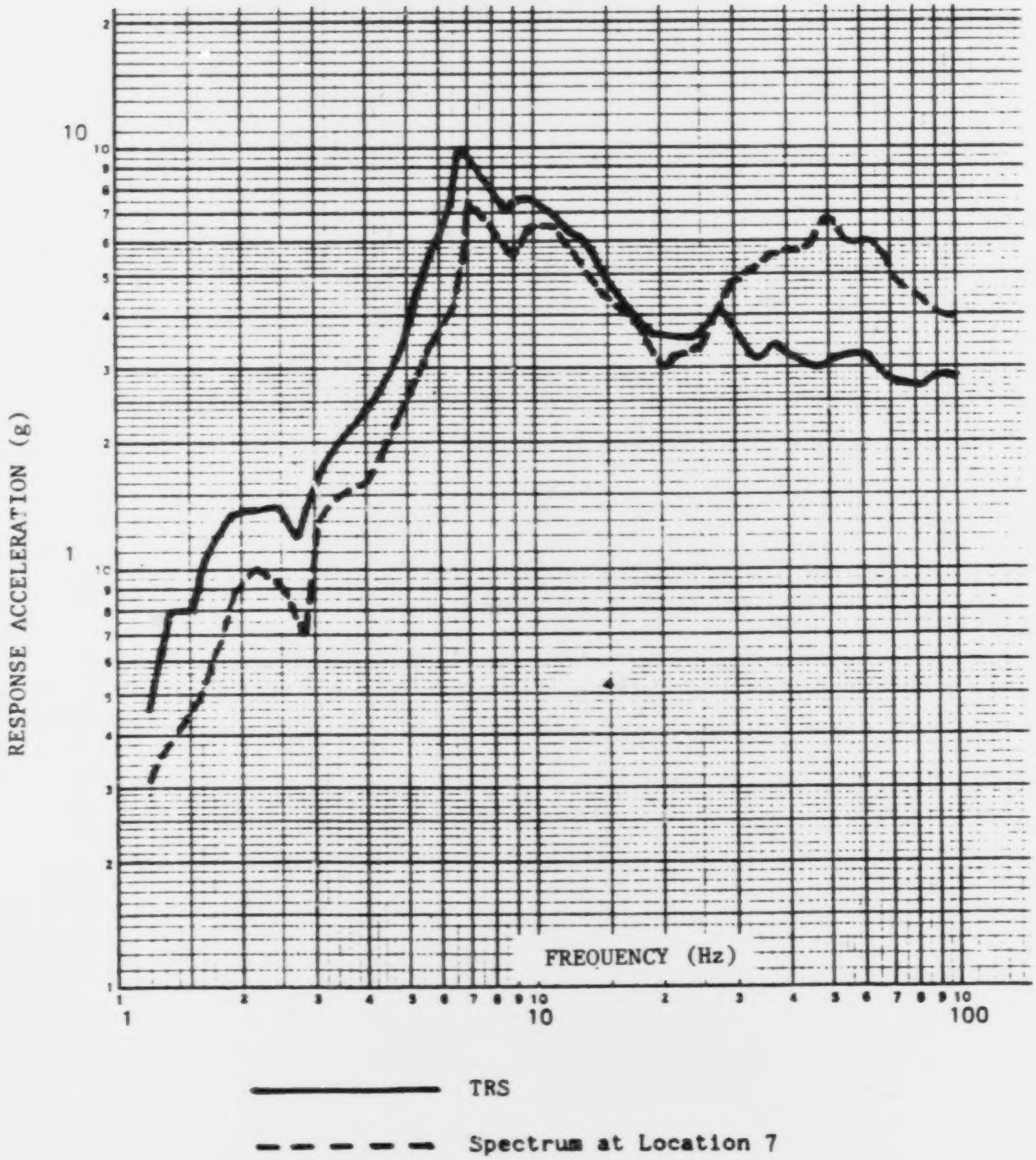

Fig. 3-9. Input motion TRS and response spectrum at switchgear Location 7 during Run 31, vertical direction (5% damping).

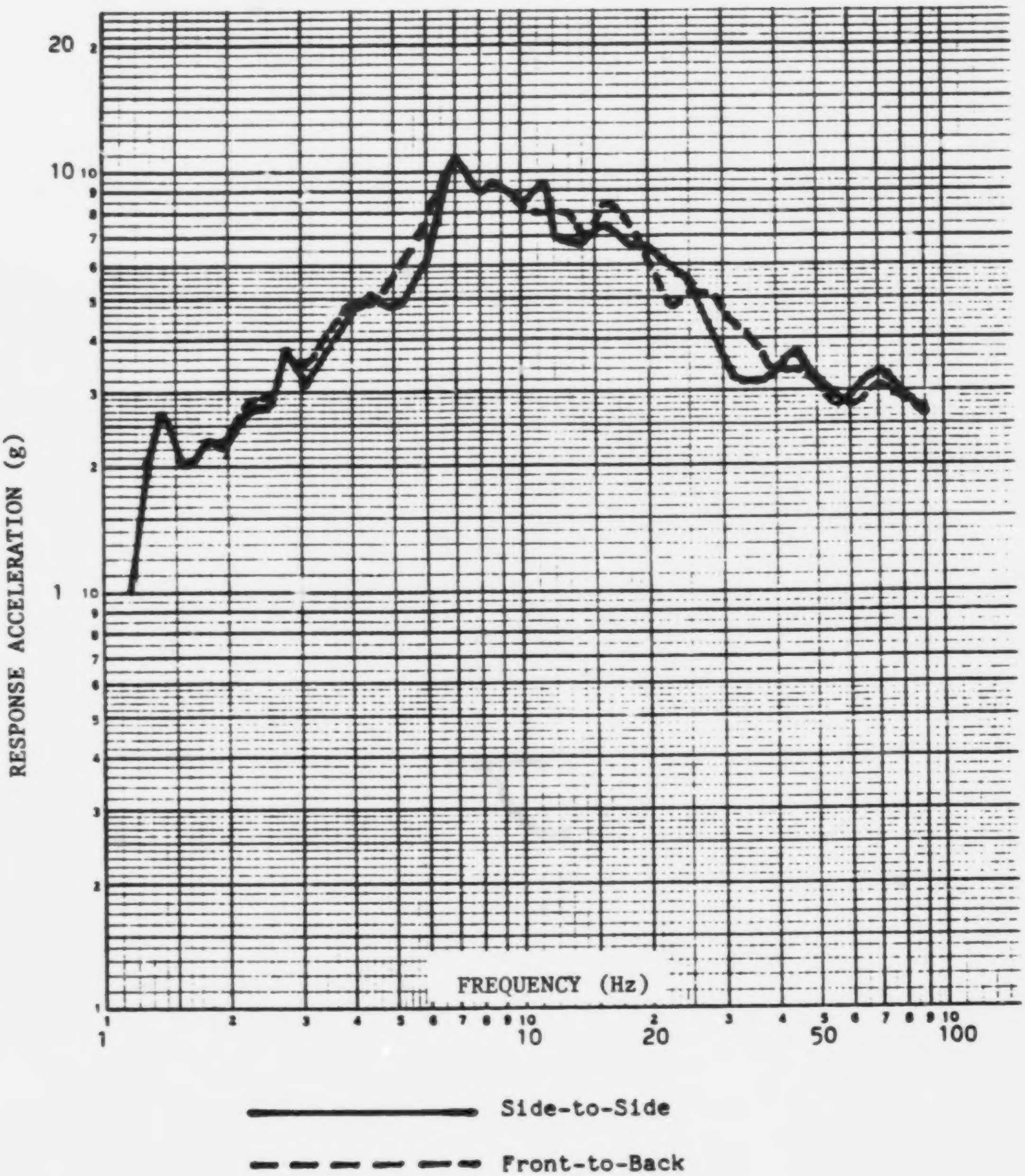

Fig. 3-10. Envelope of horizontal input motion TRS (3% damping).

121

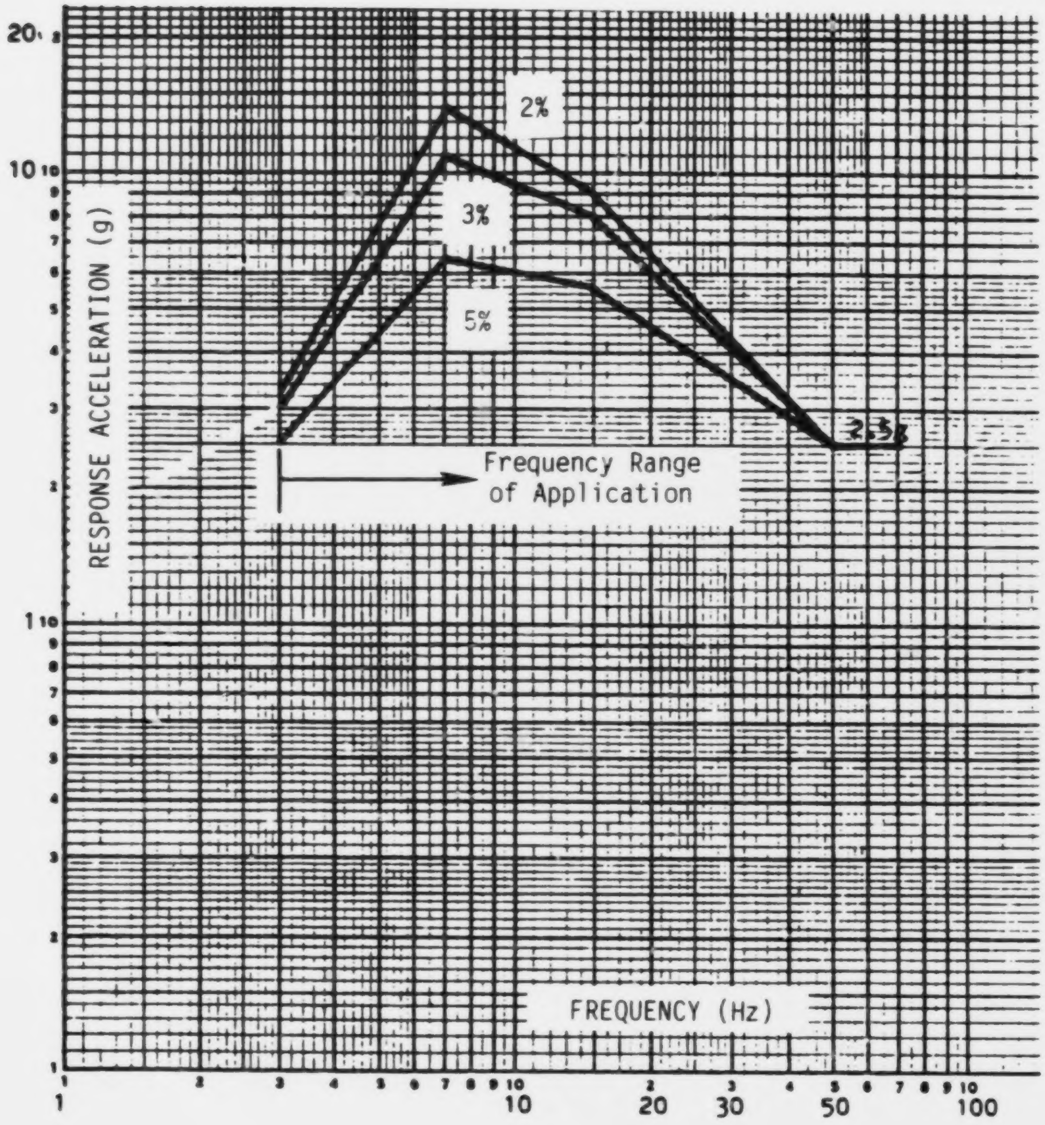

Fig. 3-11. Minimum horizontal seismic capability of the switchgear, expressed as response spectra at indicated damping values.

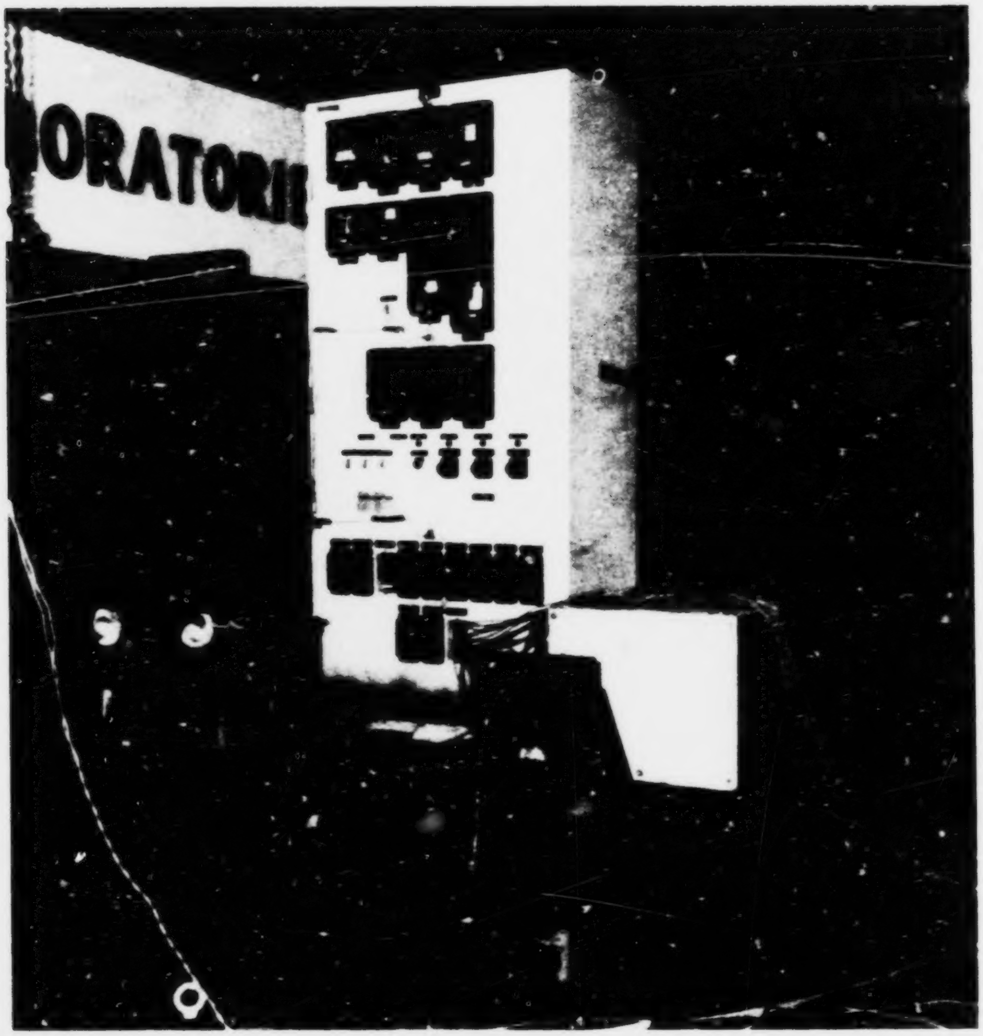

Fig. 3-12. Front view of safeguard relay board, with the 4.16 kV switchgear potential transformer mounted alongside.

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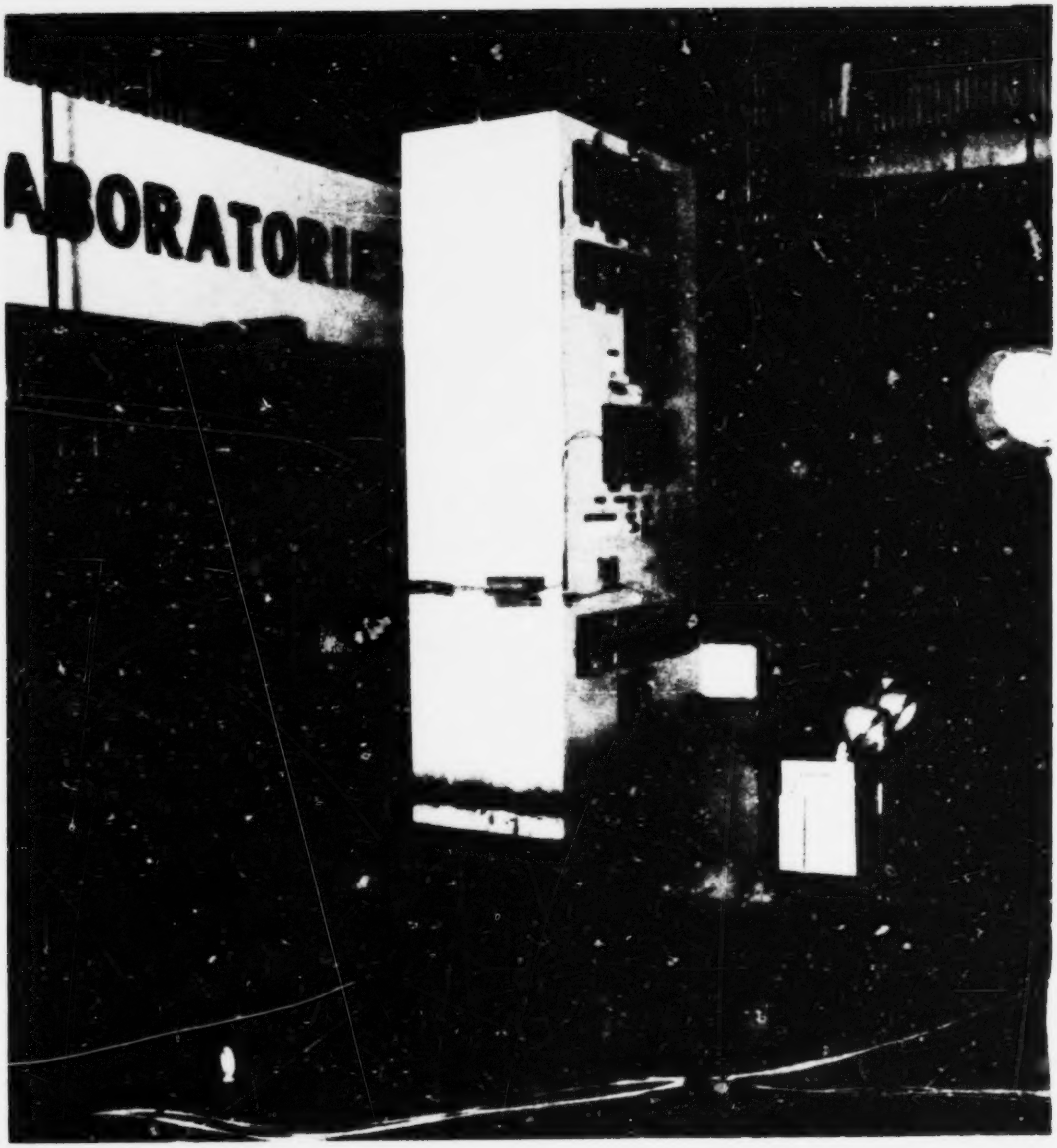

Fig. 3-13. Side view of the safeguard relay board, with the emergency light pack mounted separately in front.

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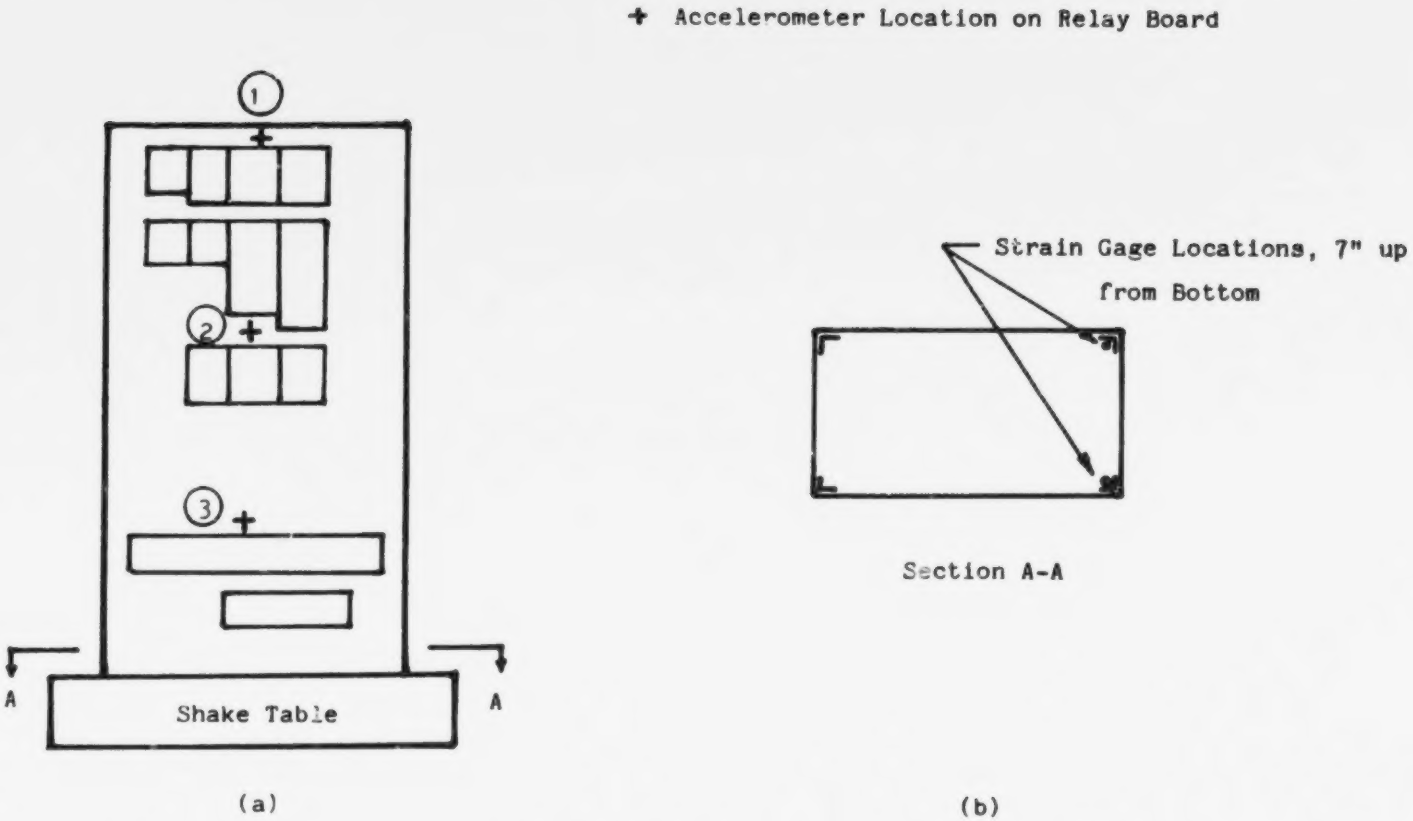
+ Accelerometer Location on Relay Board
1
2
3
A
A
Shake Table
Strain Gage Locations, 7" up from Bottom
Section A-A
(a)
(b)

Fig. 3-14. Locations of (a) accelerometers on safeguard relay board front panel and (b) strain gauges near cabinet base.

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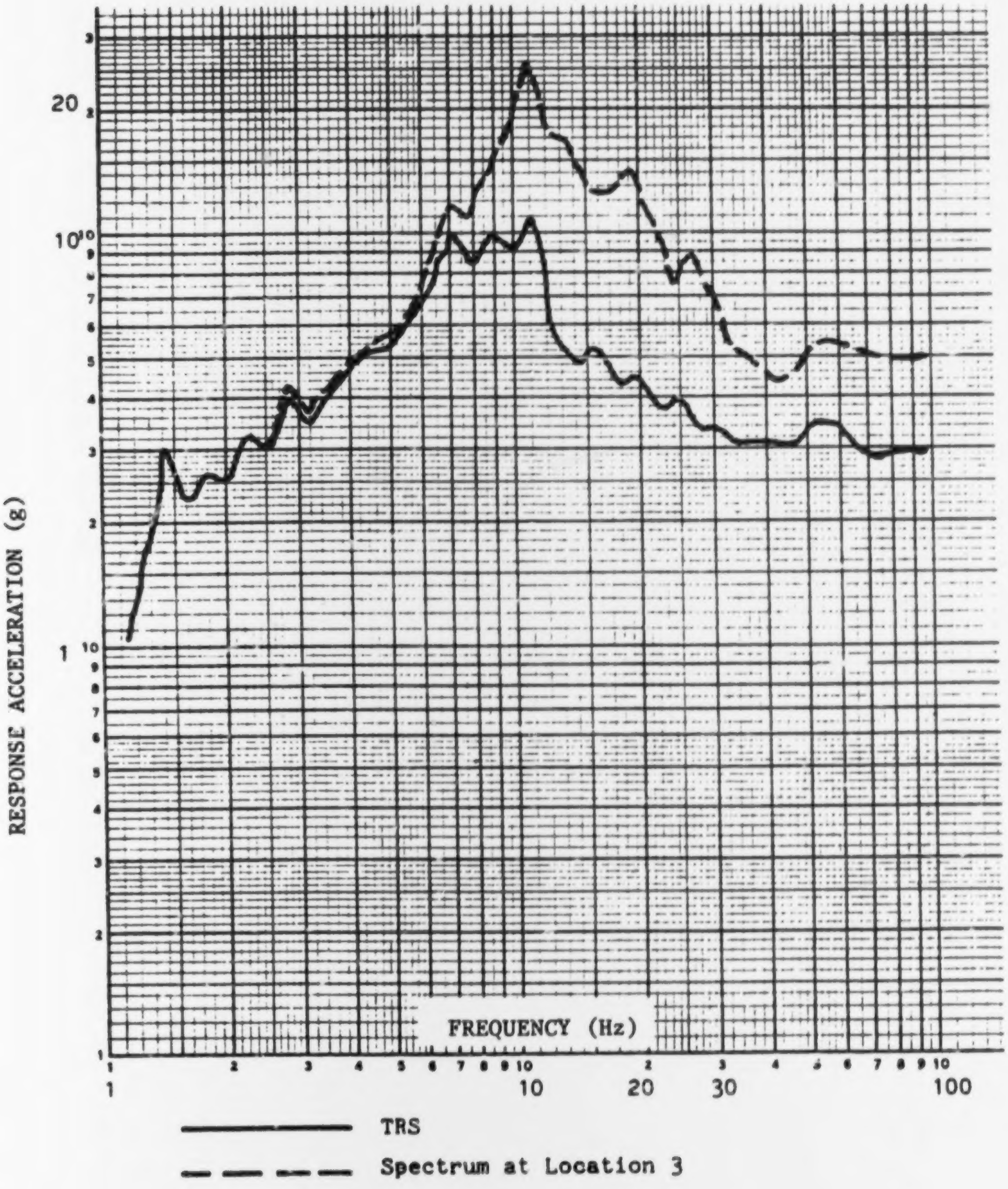

Fig. 3-15. Input motion TRS and response spectrum at relay board Location 1 during Run 14, F-B direction (3% damping).

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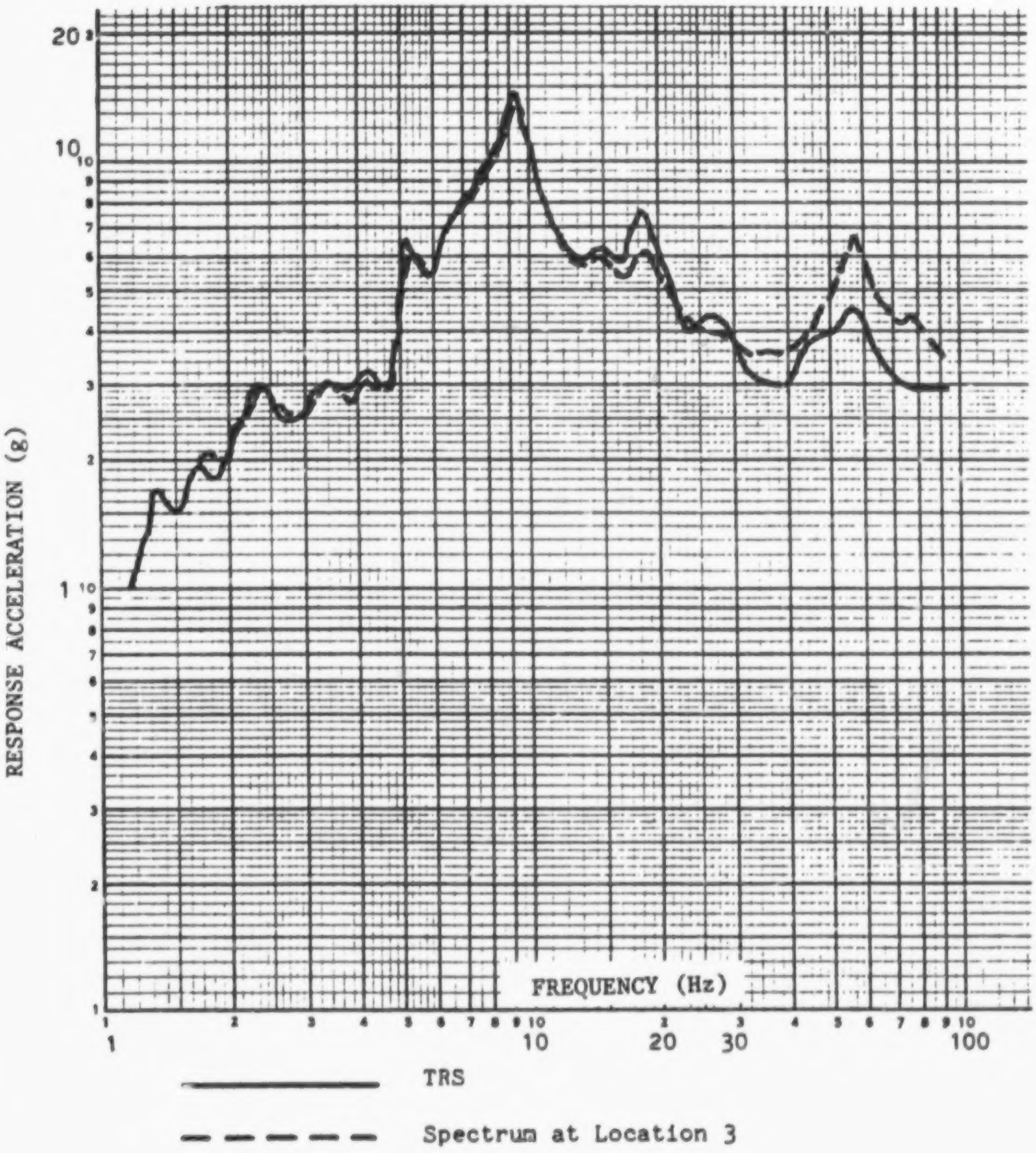

Fig. 3-16. Input motion TRS and response spectrum at relay board Location 1 during Run 14, vertical direction (3% damping).

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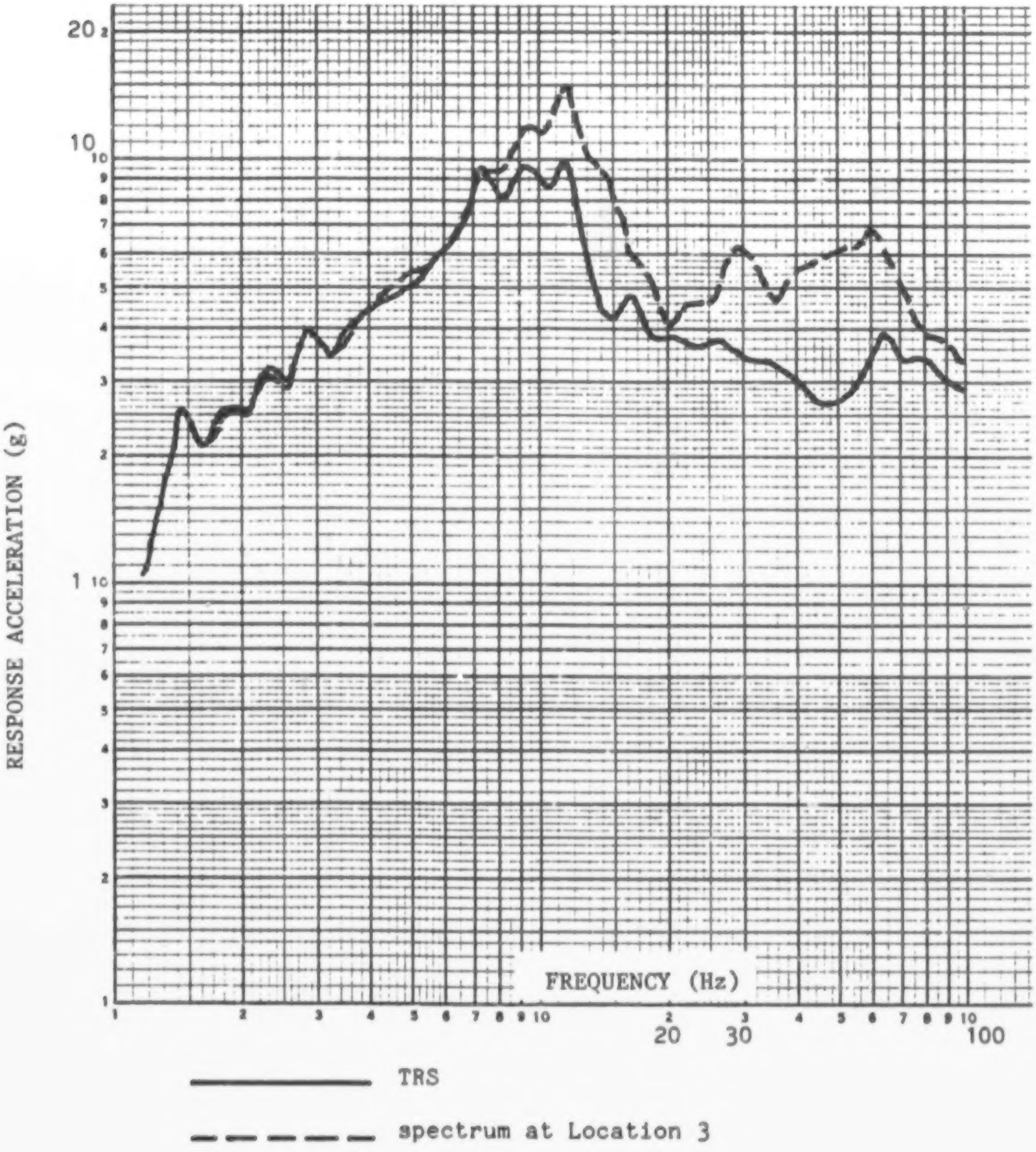

Fig. 3-17. Input motion TRS and response spectrum at relay board Location 1 during Run 27, S-S direction (3% damping).

108

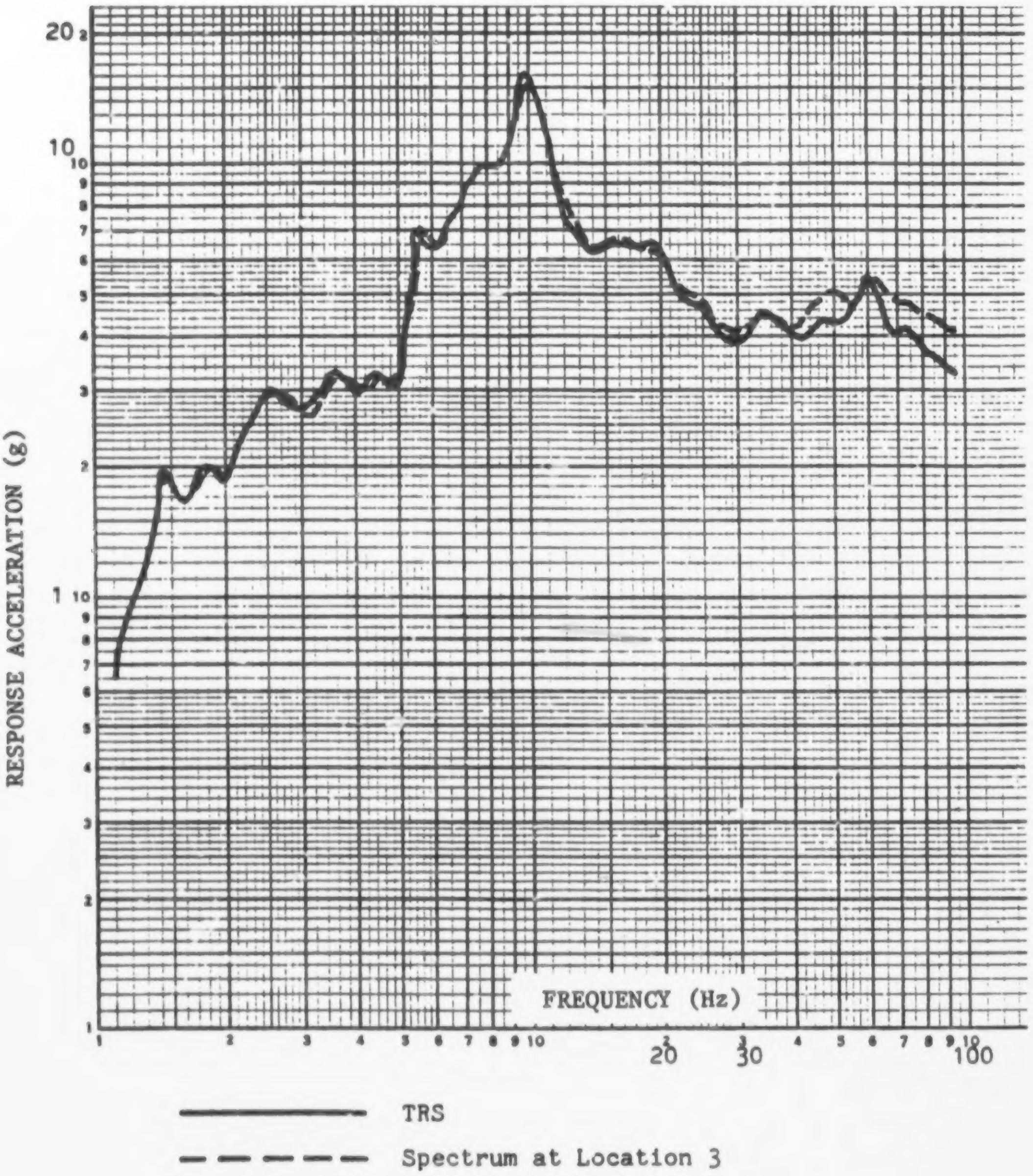

Fig. 3-18. Input motion TRS and response spectrum at relay board Location 1 during Run 14, F-B direction (3% damping).

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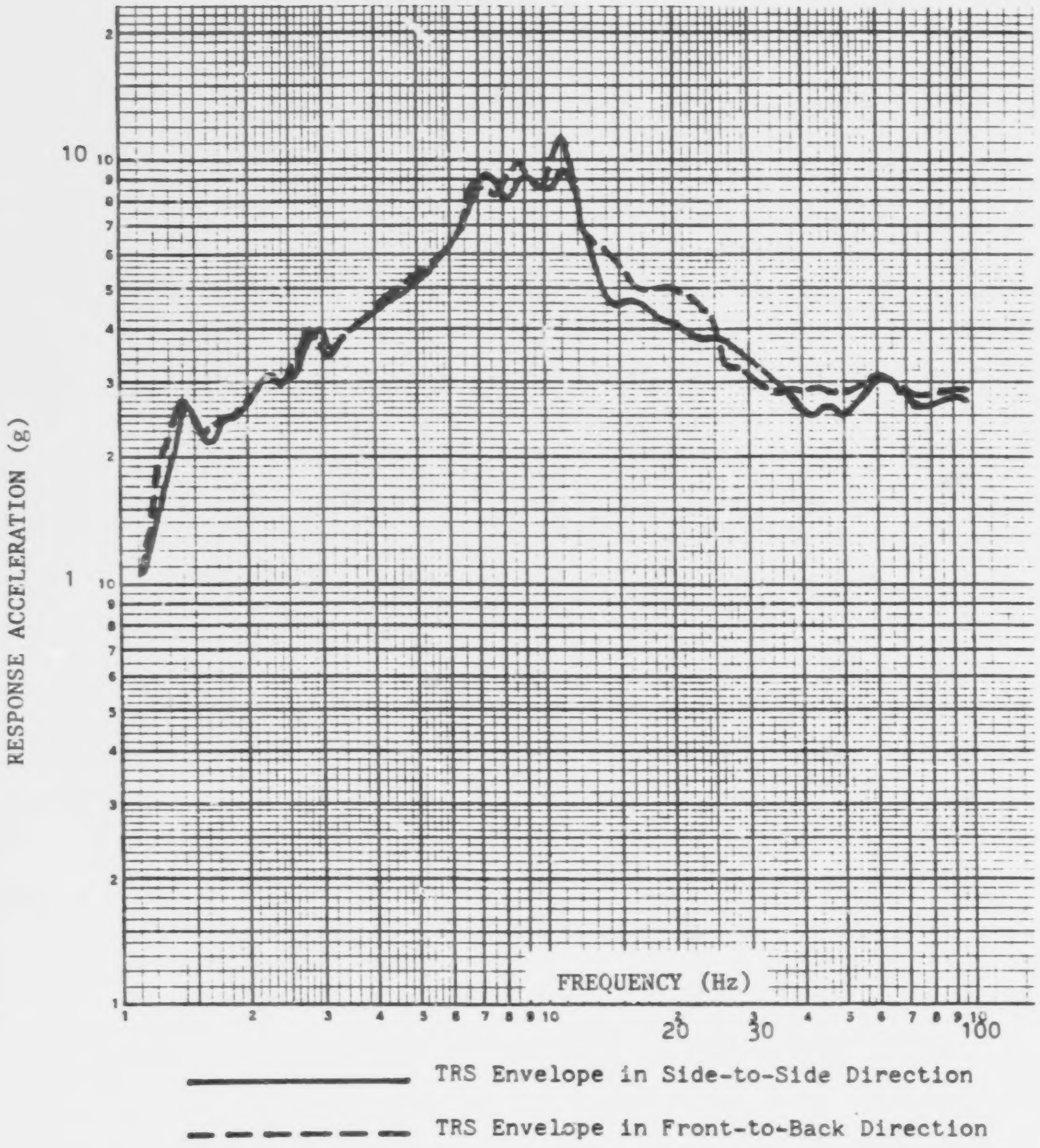

Fig. 3-19. Envelope of input motion TRS for safeguard relay board, both horizontal directions (3% damping).

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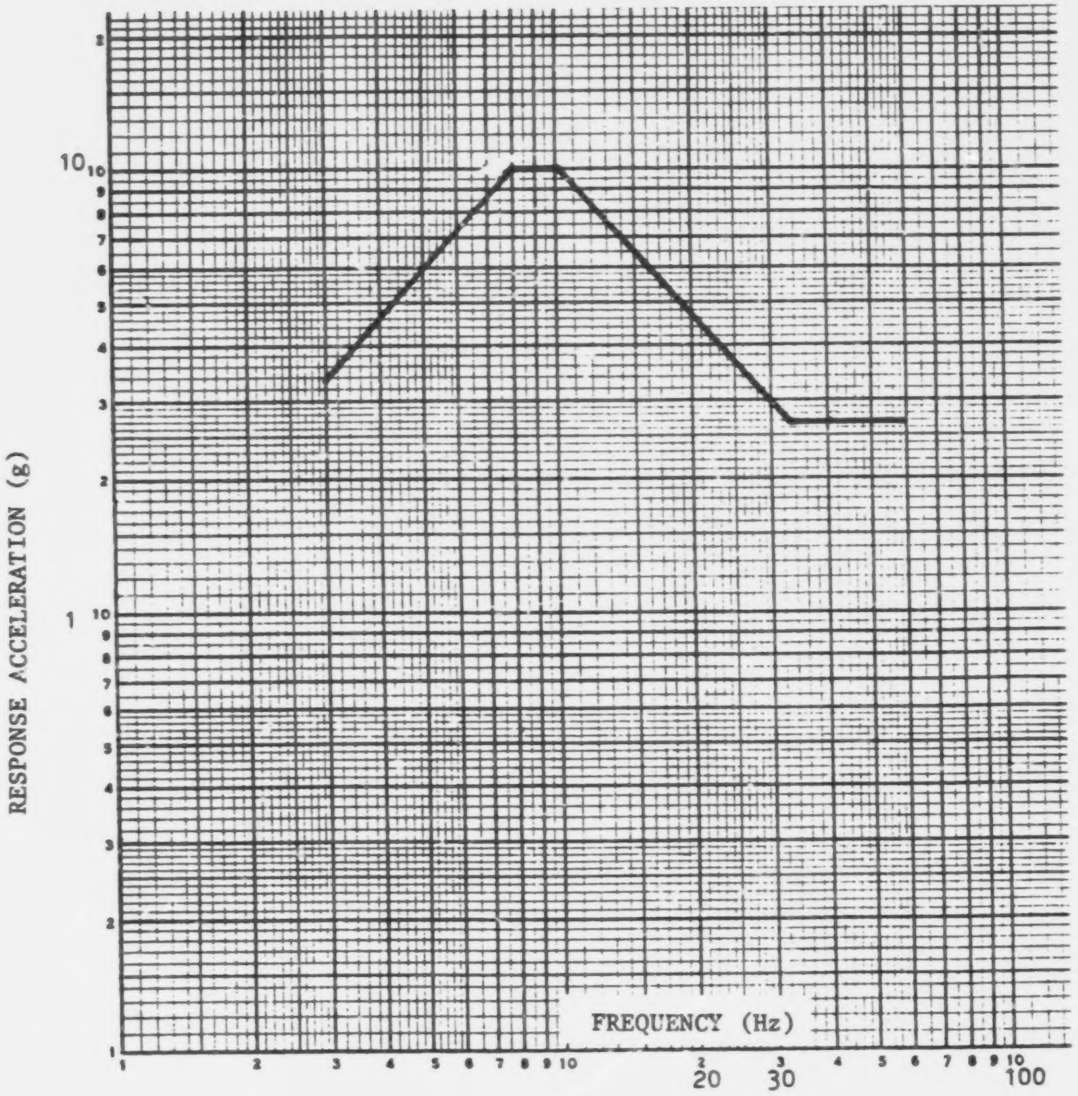

Fig. 3-20. Minimum horizontal seismic capability of the safeguard relay board, expressed as a 3% damping response spectrum.

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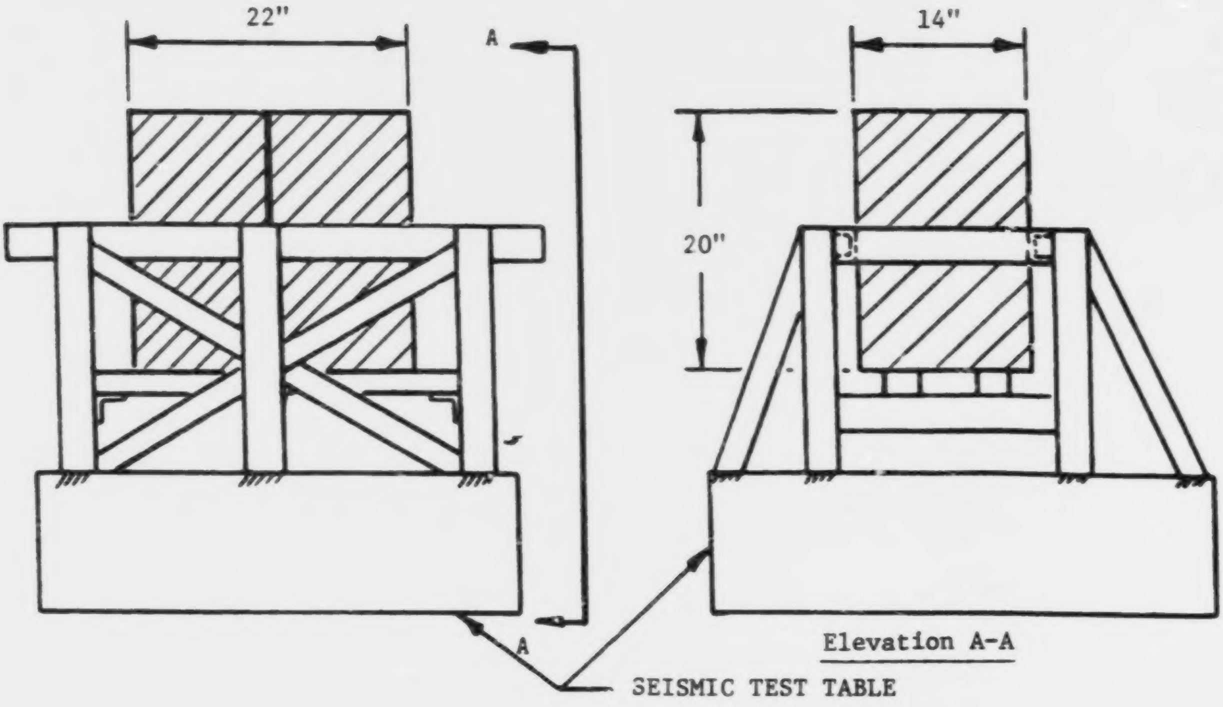
22"
A
14"
20"
A
Elevation A-A
SEISMIC TEST TABLE

Fig. 3-21. Test configuration for two battery cells and racks. Note braced modifications.

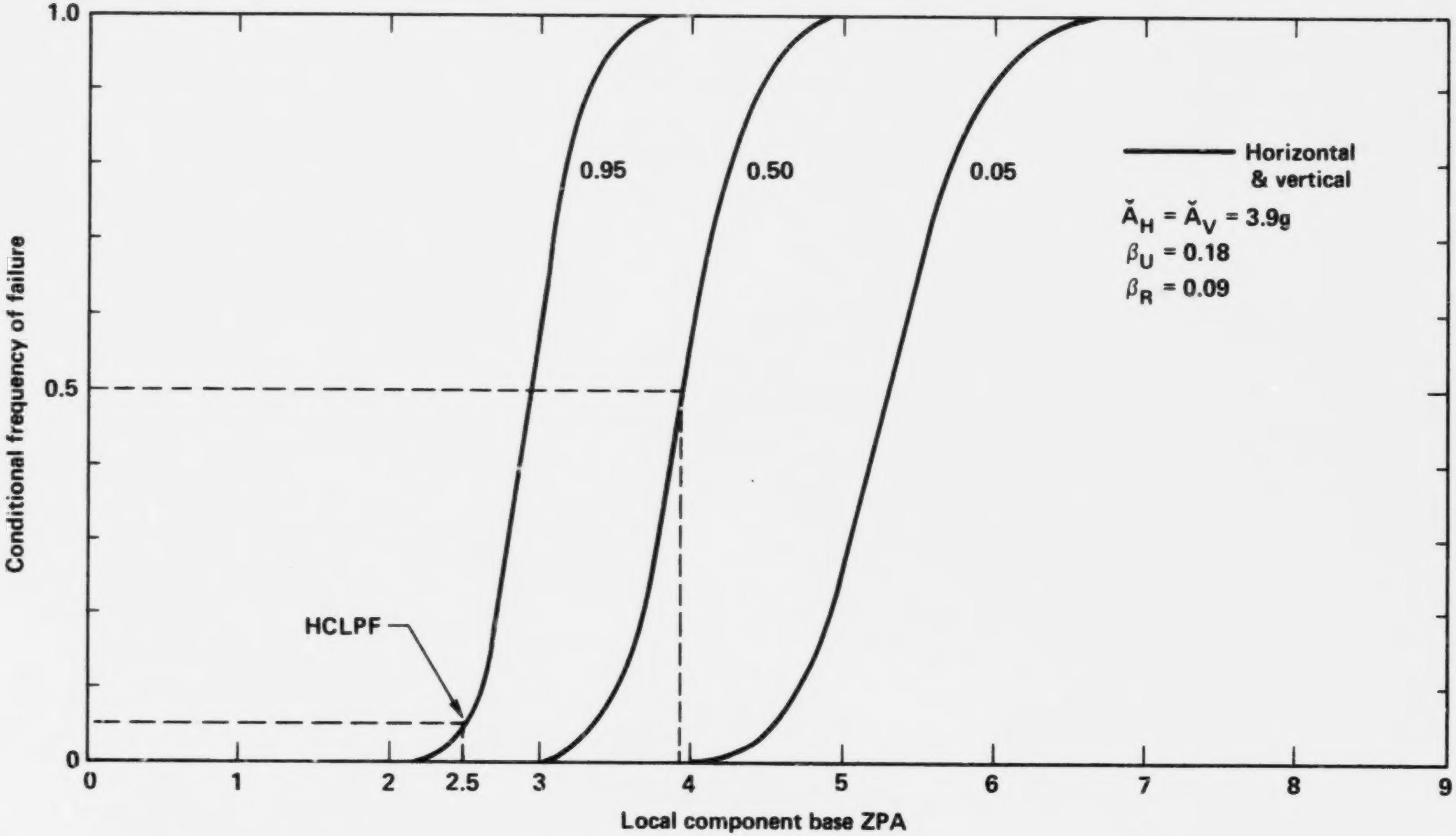

Fig. 3-22. Fragility curves for 4 kV switchgear estimated from results of qualification testing.

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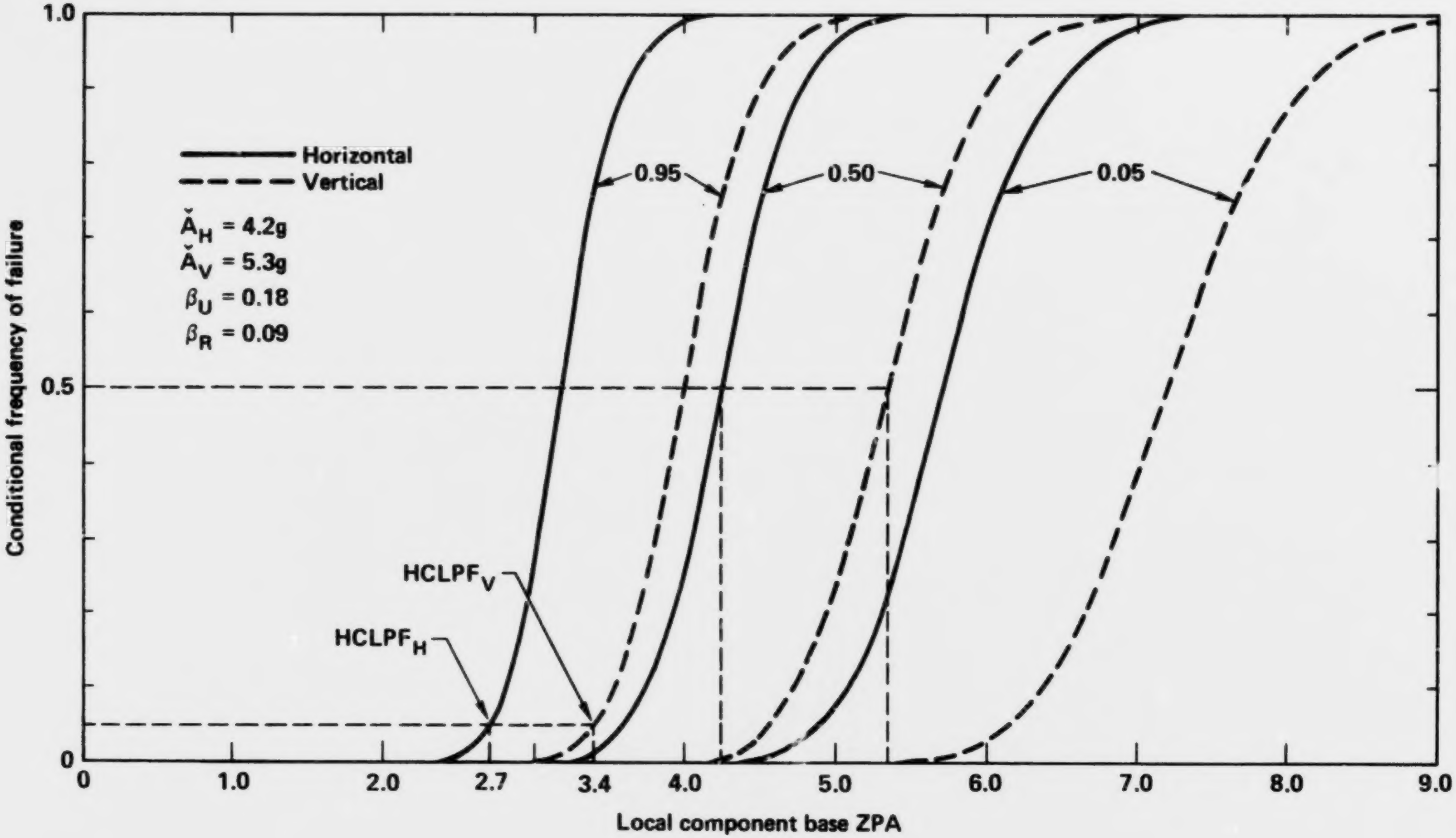

Fig. 3-23. Estimated fragility curves for potential transformer, safeguard relay board, and emergency light battery pack.

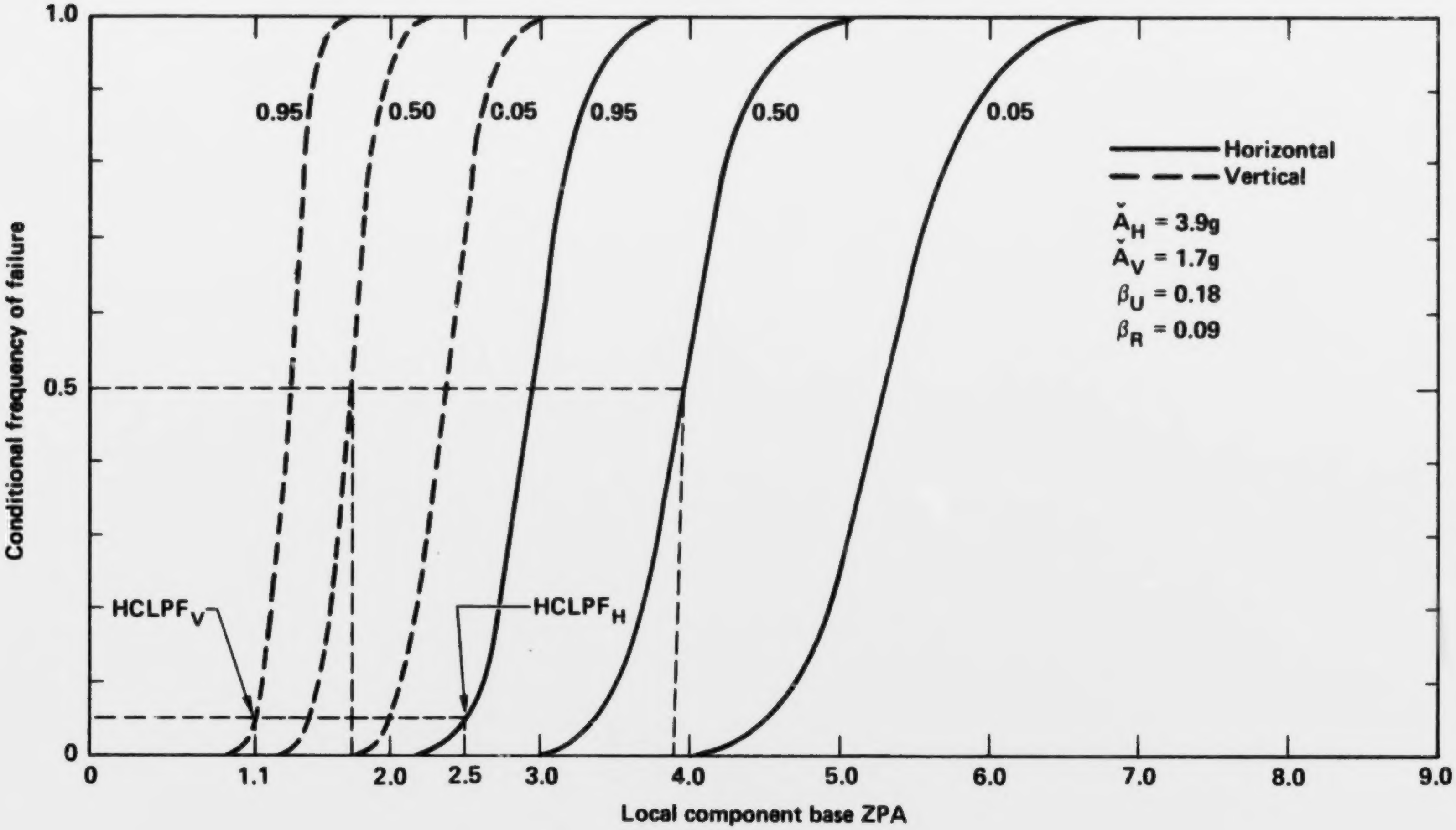

Fig. 3-24. Estimated fragility curves for station battery and racks.

4. SUMMARY AND CONCLUSIONS

4.1 Component Prioritization

As part of our Phase I CFRP activities we systematically identified and categorized electrical and mechanical components influencing plant safety. Based largely on expert opinion drawn from several sources within the nuclear industry, we first identified plant systems relevant to plant safety. Within each system we then ranked each component according to a combination of (1) its importance to overall system function, and (2) its anticipated seismic capacity. Importance was denoted by importance groups "VI", "I", and "LI" (signifying "very important", "important", and "less important" components, respectively), seismic capacity by levels 1, 2, and 3 ("high-", "intermediate-", and "low-capacity" components, respectively).

The results of our component prioritization efforts yielded the following general observations:

- virtually all "very important, low-capacity" components (i.e., in ranking group "VI-3") comprise electrical equipment. Most "standard" items of mechanical equipment (e.g., pumps, valves) rated as "very important" were also expected to be Seismic Level 1 ("high" capacity), with the exception of relief valves which were assigned to Seismic Level 2 ("intermediate" capacity). This result reflected the general opinion that power supply and control, and not inertial loads, more seriously affected the availability of such components during or following an earthquake.

- in many cases, the "high capacity" ranking of these "standard items" was supported by the Millstone qualification data, despite the relatively low (0.18g) SSE requirement. Not surprisingly, however, much of the qualification testing did not reach the threshold ZPA that we had designated for Level 1 components (i.e., 2g) owing to the low SSE requirement. This result suggests that review of additional data is needed, preferably "high-level" qualification data (e.g., Diablo Canyon).

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- of the "VI-3" components, medium-voltage (4 kV) metal-clad switchgear was generally regarded of highest priority for Phase II testing owing to (1) its importance for supplying plant electrical power and (2) its sensitivity to high seismic accelerations as evidenced by high-level qualification testing. In general, the "VI-3" components show a strong bias towards contact-operated electrical devices (e.g., relays, contactors).

In general, we have assigned the highest priority for comprehensive Phase II testing to the components in ranking group VI-3. A subset of specific components recommended for Phase II testing, discussed in Section 5 of this report, includes the following listed in order of priority: 4 kV switchgear, ESF sequencers, safety relay boards, local starters, electrical distribution equipment, and battery chargers. These particular components were selected in part because each in its own right is regarded as having an important safety function. Combined with the results of our Phase I motor control center tests, fragility investigations of these components would yield valuable additional data on the behavior of common internal devices (e.g., relays, contactors) in a wide variety of configurations.

As discussed earlier in Section 2, we assigned second priority to equipment included in the I-3 ("important, low-capacity") and VI-2 ("very important, intermediate-capacity") ranking groups.

For the remaining components, work should be continued in Phase II to obtain data "confirming" the seismic capacity levels identified during Phase I. If, particularly for "high-capacity" components, we are unable to confirm capacity through existing data, these components may then become candidates (albeit lower-priority ones) for future testing.

717

4.2 Development of Fragilities from Existing Data

To demonstrate how "high-level" excitation testing can be used to infer ultimate seismic capacity, we assessed in detail five components actually tested as part of the Hosgri seismic evaluation performed by the Pacific Gas & Electric Company for Diablo Canyon. The results of our assessment indicated the following:

- in principle, a "HCLPF" approach can be used to infer ultimate capacity provided sufficient information is available from which to estimate how various factors affect seismic performance. These factors include not only specific hardware modifications made to enhance seismic performance, but also how the component is mounted. The capacity estimate may, however, be non-conservative (i.e., an overestimate of capacity) depending on the parameters β_R and β_U selected to represent, respectively, random and modeling uncertainty.

- many components included in the Hosgri evaluation were qualified in their standard commercial configurations or with relatively minor modifications. This result is encouraging because it suggests commonality among certain "standard" equipment items and therefore the applicability of "high level" test results to like equipment at plants having lower SSE requirements.

- a detailed evaluation of high-level data can suggest component modifications that may significantly increase seismic capacity, or areas of emphasis in seismic margins reviews.

Information is available to us from PG&E on many Diablo Canyon components not tested as part of the Hosgri requalification program because the results of prior qualification tests (based on a 0.4g peak ground acceleration SSE) met the more stringent requirements imposed by the Hosgri earthquake. Work will continue in Phase II to use this data for inferring the seismic capacity of selected mechanical and electrical components.

4.3 Conclusions

The results of our Phase I prioritization efforts provide guidance regarding not only the urgency of assessing the seismic performance of various mechanical and electrical components, but also the nature and rigor of assessment procedures appropriate for the component in question. Options available for detailed assessment include comprehensive testing -- such as the parametric motor control center tests that we performed in our Phase I demonstration test program -- or evaluation of existing data, or some combination of the two. Our Phase I efforts have demonstrated that if appropriate data is available, either from existing sources or from specially-designed fragility test programs, insights into component capacity can be obtained and serviceable fragility functions can be generated for PRA applications. The question that remains, however, is one of how definitive the resultant descriptions of seismic performance actually are.

As discussed in Section 1, a "bottom-up" assessment of seismic capacity (i.e., fragility level estimated from HCLPF capacity) suggests that fragility level increases with uncertainty, which is clearly non-conservative. The fragility analyst must therefore exercise extreme care when selecting the uncertainty parameters used to infer the ultimate capacity, or "fragility level", of a component. Unfortunately, the information necessary to select these parameters may not be available from existing data, or may be difficult to assess consistently if attempts are made to consolidate data from several diverse sources. The less definitive the data on HCLPF-derived fragility descriptions are based, the higher their degree of inherent uncertainty.

For certain high-capacity components, this uncertainty may be tolerable if only a "lower bound" fragility -- a HCLPF capacity, for example, or a 95% fragility function -- is adequate for regulatory decision-making or for PRA applications. This may apply, for example, to the five Diablo Canyon components considered in this assessment. This may also be true for high-capacity components at plant sites with relatively low SSE requirements (e.g., in the eastern U.S.), provided that (1) the "high capacity" rating of these components can be substantiated, and (2) commonality in configuration and mounting conditions can be established between the in-plant components in question and those for which "high level" data is available.

In general, however, high inherent uncertainty implies that a "top-down" assessment -- estimating HCLPF capacities from measured fragility levels -- is still preferable for assessing seismic performance. This is particularly true when a detailed fragility function, rather than a "threshold" fragility description, is necessary for low-capacity equipment. Parametric "sensitivity" tests, even on a limited scale, are best-suited for this purpose when structured to systematically investigate how individual factors affect seismic performance. The resultant understanding aids not only in developing fragility descriptions directly from the failure data, but also in interpreting and applying data compiled from other sources.

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5. RECOMMENDATIONS FOR PHASE II

5.1 General Approach to Fragilities Testing

As the introduction to this report discussed, resource and time constraints make it impractical to explicitly develop meaningful fragility descriptions by empirical means alone. Even for nominally identical components, variations among models and manufacturers, and in mounting and loading conditions imply that any fragility estimate will be based in large part on engineering judgement. Meaningful yet cost-effective fragilities testing can, however, be conducted within these constraints if it seeks not to explicitly develop "generic fragilities" broadly applicable to wide ranges of components, but rather to enhance understanding of how certain components fail ("failure modes"), what the important factors are that affect component performance, and what the relative influence of these factors is.

Testing in the form of "sensitivity studies" provides one method of gaining this understanding. In our Phase I demonstration tests, for example, we investigated the effect of "base flexibility" on MCC behavior (primarily for electrical devices but also for the cabinet itself) through a carefully structured series of sensitivity tests. The test results provided actual seismic capacities of the specific components tested, as well as a basis for estimating "single-parameter" fragility descriptions (i.e., referenced to local ZPA) including confidence limits and practical "lower bound" (i.e., HCLPF) seismic capacities. The tests also suggested possible hardware modifications to increase seismic capacity, such as top bracing of the cabinet or use of reed-rather than armature-type relays. More importantly perhaps, the test results suggest that other descriptions of fragility -- incorporating frequency effects, for example -- might be "more appropriate" for characterizing component behavior.

These tests showed that meaningful fragilities testing can be conducted within practical constraints if it focuses on understanding how various factors influence component behavior rather than on developing fragilities explicitly. Our Phase I experience therefore suggests that Phase II tests be similarly conducted according to the following general steps:

(1) identify a representative component or sample of components for testing. Such a sample might not necessarily be "generic" in the purest statistical sense, but should attempt to include significant variations within a given component type (armature- vs reed-type relays, for example).

(2) identify failure modes and the relevant forcing or response functions. Characterize "failure" (either functional or physical) in terms of a suitable parameter that can be measured experimentally.

(3) identify factors or "technical issues" affecting component failure; such factors might include, but not necessarily be limited to, variations in mounting, input motion, and component damping. Design the experimental program to parametrically vary those factors judged to most significantly influence seismic performance.

(4) perform tests to identify when failure occurs, i.e., component median capacity. Such tests might, for example, follow qualification procedures (e.g., use of same input spectra) but at elevated input motion levels. Alternatively (particularly for "high capacity" components), test to a pre-determined level to establish a "lower bound" failure threshold.

(5) use test results to empirically estimate median capacity; note that this result is equivalent to the deterministic "fragility level" generated as a part of some qualification tests. Based on component behavior over all conditions considered, develop estimates of random variability and modeling uncertainty in the empirically derived median capacity.

Although this approach does not remove subjectivity from the process of describing component fragility, it does improve the basis on which these judgements are made. Furthermore, it can provide an improved basis for interpreting data from other sources or for defining test conditions if more rigorous testing of a specific component is necessary.

5.2 Recommendations for Phase II Testing

The following discussion lists, in order of priority, the major components proposed for inclusion in the Phase II CFRP testing program.

5.2.1 Medium-Voltage (4 kV) Switchgear

Typical equipment consists of a large breaker located at the bottom of the cabinet with protective signal relays mounted above and sometimes in the door panel. The main breaker attachment is either a sliding bar arrangement or the breaker is locked into position by the use of jack screws. The primary concern here is mainly structural integrity of the locking and support mechanisms during seismic excitation. This issue may well define the selection of the equipment (General Electric, Westinghouse, or ITE). The main breaker itself may not be susceptible to the seismic environment with the possible exception of the arc chutes near the breaker contacts which have failed structurally in past tests due to vibration.

Technical Issues

One important issue is the mounting of the equipment to simulate line-up of switchgear in plant installations. It is proposed that side stiffening be used to simulate neighboring cabinets and provide the appropriate stiffness. The necessary fixture design needs to be addressed during pretest planning to achieve proper simulation. Limited finite-element modeling may be appropriate to investigate the structural response characteristics. During the equipment selection phase, the different breaker attachment methods will also be further investigated to arrive at the proper selection considering such elements as susceptibility of the attachment to structural failure, older designs versus currently available equipment, and the structural vulnerability of main breaker elements themselves. It is possible that no clear advantage be demonstrated for the selection of either breaker mounting method and that two types representing different installation types need to be tested.

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Additional issues which need to be considered are the configuration of top bus bar assemblies for the incoming power and the routing and attachment of the 4 kV cables at the bottom or rear panel of the switchgear. Some simulation of the top bus bar assembly may be desirable and its configuration and extent of inclusion in the test program must be defined during the planning phase. Potential transformers, relays and current transformers may exhibit weaknesses in their structural attachment points and should be included in the evaluation. It may be desirable to interchange individual components from other switchgear designs to provide as extensive a data base as possible from a single test configuration.

In addition to the structural considerations, relay chatter of the auxiliary relays is of importance in establishing fragility of this equipment. Hence, the relay characteristics, their mounting location, and any known susceptibility to chatter need to be considered during test planning.

5.2.2 Emergency Safety Function Sequencer

This group of equipment consists of mechanical or solid state devices which control individual safety functions. Equipment is generally mounted in medium size cabinets. Issues in general are structural susceptibility of cabinet mounting, attachment and locking of circuit cards, susceptibility of individual components and electrical connections to vibration induced failure, and chatter of relay contacts in those installations where mechanical type relays are used. Selection of the appropriate test items is of importance and possibly a test cabinet should be configured which will include the items of importance to various plant designs.

5.2.3 Safety Relay Board

Safety relays boards are generally mounted in separate enclosures and consist of a number of relays sensing various input signals. The design and configuration of these boards is unique for each plant. The general design of these cabinets and the individual components (relays) are quite similar to items which have been tested in the past. The issue then becomes one of what additional information on fragility of relays, components and enclosures can be obtained over what is available and what will be determined from the ESFS investigations. A particular test configuration may evolve which may warrant separate testing.

5.2.4 Local Starters

This equipment is generally mounted inside smaller enclosures. Again, the issues are structural susceptibility and opening and closing of contacts. In general, this type of equipment is "ruggedized". Test equipment needs to be selected based upon its construction and use in plants.

5.2.5 Electrical Distribution Equipment

Breakers, located within this equipment, are frequently mounted on slides; hence, their mounting and attachment may be susceptible to seismic excitation. The equipment is generally heavier than motor control centers but lighter than 4 kV switchgear. The issues here are also structural integrity and chatter of breaker contacts. Appropriate equipment needs to be selected for testing and proper mounting simulation for equipment installation on the seismic table must be defined.

5.2.6 Battery Chargers

Battery charging equipment consists of transformers, rectifiers, relays and control devices which are mounted inside an enclosure. The issues, as for the previous equipments, are structural integrity and contact chatter. Test planning will encompass review of plant-installed equipment, selection of components to be tested, and definition of the test configuration.

5.3 Testing Alternatives

In principle, the "sensitivity study" concept can apply to the interpretation of existing (e.g., qualification) data as well, provided that (1) the input motions are sufficiently severe to cover earthquake levels of regulatory interest, and (2) sufficient detailed information is available for characterizing how certain factors -- mounting, for example -- affect seismic performance. As part of our Phase I prioritization activities, for example, we developed fragility descriptions for five Diablo Canyon components on high-level response data from the PG&E Hosgri seismic requalification program. Although not true "fragility" data, the input motions were sufficiently high to produce useful information on component behavior under conditions well in excess of those anticipated for any "reasonable" increase in design earthquake levels for eastern plant sites. Following the approach detailed in Section 3, we assumed for each component that its qualification level defined a "high-confidence, low probability of failure" (HCLPF) capacity. Aside from providing a basis for developing probabilistic fragility descriptions, the PG&E tests yielded insight into the influence of parameters such as support arrangement, cabinet rigidity and mass distribution on seismic capacity. In some cases the results of these tests identified practical -- and often relatively minor -- hardware modifications which substantially improved the seismic performance of the equipment tested.

It is important to note, however, that evaluation of existing data may not be suitable if truly definitive fragility functions are necessary. Two factors contribute to a relatively high degree of uncertainty in fragility functions derived solely from existing data:

(1) using qualification data to infer median capacity by means of a "HCLPF" approach suggests -- non-conservatively -- that fragility level increases as random and modeling uncertainties increase. Consequently, the fragility analyst must use extreme care when selecting the uncertainly parameters that define the fragility function.

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(2) qualification tests do not typically include systematic (i.e., parametric) investigations of factors that potentially affect seismic performance -- mounting conditions, for example. Any "sensitivity studies" during such tests usually arise out of necessity as equipment is modified to meet qualification requirements. As a result, often only minimal detailed information is available for estimating the uncertainty parameters defining the fragility function.

This latter problem may further complicate matters if data (even true "fragility" data) from several sources are consolidated into "generic" fragility functions for broad classes of equipment. Without detailed information how particular test conditions -- especially changes in test conditions -- affect component behavior, it is difficult to arrive at a fragility description that does not have a high degree of inherent uncertainty.

In cases where "threshold" fragilities may be adequate for making regulatory decisions -- those involving "high capacity" components, for example -- high-level data may provide reasonable HCLPF capacities and thus avoid or minimize testing. Fragility curves derived from qualification data (i.e., by a HCLPF approach) can also provide serviceable PRA input if their high inherent uncertainty can be tolerated. Such might be the case, for example, if only the lower portion of the fragility function were needed in the risk assessment. However, parametric testing, even on a limited scale, is still preferable for assessing seismic performance, particularly for low-capacity equipment where a more complete fragility description may be necessary.

Clearly, even for functionally identical components, variations among manufacturers and models, in size and type, and in mounting and loading conditions imply that any fragility estimate -- or, for that matter, other methods of assessing component performance -- will be based to a certain extent on engineering judgement. It is important that this judgement be supported by as firm a technical basis as possible within practical

AVAILABLE

137

constraints. Testing for "understanding" rather than for broadly-applicable "generic" fragilities can yield information that is useful on many levels. This information can provide:

- guidance to the fragility analyst as to what should be considered in developing a specific fragility description for a specific component. If properly structured, tests can also provide insight into broader applicability of fragilities for "similar" types of components, even if these fragilities are not necessarily generic in the strictest statistical sense.

- improved understanding of component failure modes and the factors that most significantly affect the seismic performance. This understanding may in turn suggest hardware modifications, in some cases relatively minor, for enhancing the seismic capacity of critical components.

- an improved basis for interpreting and applying test data obtained from existing sources, particularly for assessing the extent to which the data addresses specific factors affecting seismic performance. This understanding is necessary for describing uncertainty in a fragility function derived from experimental data, and is especially important qualification data is used to infer ultimate capacity (e.g., through a "HCLPF" approach) or when consolidating equipment data from several sources.

- an improved basis for defining test conditions if more rigorous testing of a specific component is required.

- guidance for developing screening techniques for reviewing actual plant equipment ("walkdown" procedures).

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It is also important that such testing be viewed not necessarily as a replacement for, but also as a supplement to, evaluation of data from other sources.

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APPENDIX A

Component Ranking Matrix

SYSTEM COMPONENT	Seismic Capacity Level	Control Rod Insertion	Accident Boration	CVCS (Letdown)	CVCS (Seal Injection)	Safety Injection System	RCS Pressure Relief	RCS	Residual Heat Removal System	Main Steam System	Auxiliary Feedwater System	RCS/MS Pressure Relief	Containment Spray System	Reactor Containment Fan Coolers	HVAC Systems	Purge System	Containment Isolation System	Isolation Valve Seal Water System	Penetration Pressurization System	Component Cooling Water System	Service Water System	On-Site AC Power System	On-Site DC Power System	Instrumentation and Controls	Chilled Water System	Diesel Oil Systems	Peripherals	Fire Protection System
Control rod drive mechanisms	X	VI																										
CRDM motor generator sets	X																											
Reactor trip breakers	2																											
Rod position indication	X																											
Rod bottom indication	2-3	LI																										
CRD system (BWR)	1	VI																										
Charging pumps/drives	1		VI		VI																							
Motor-operated valves	1		VI			VI	I				VI		VI				VI			VI	VI							
Check valves	1		VI			VI	VI	VI	VI		VI							VI										
Explosive valves (BWR)	1		VI																									
Pressure relief valves (BWR)	2		I																									
Air-operated flow control valves	1			X	VI				VI		VI																	
Reactor coolant filters	X																											
Isolation valves	1			VI																								
Seal injection filters	2				I																							
Safety injection pumps/drives	1					VI																						
Vacuum relief valves	2					I																						

COMPONENT \ SYSTEM	Seismic Capacity Level	Control Rod Insertion	Accident Boration	CVCS (Letdown)	CVCS (Seal Injection)	Safety Injection System	RCS Pressure Relief	RCS	Residual Heat Removal System	Main Steam System	Auxiliary Feedwater System	RCS/MS Pressure Relief	Containment Spray System	Reactor Containment Fan Coolers	HVAC Systems	Purge System	Containment Isolation System	Isolation Valve Seal Water System	Penetration Pressurization System	Component Cooling Water System	Service Water System	On-Site AC Power System	On-Site DC Power System	Instrumentation and Controls	Chilled Water System	Diesel Oil Systems	Peripherals	Fire Protection System
Residual heat removal pumps/drives	1					VI			VI																			
Core spray pumps/drives	1					VI																						
Power-operated relief valves	2						I					VI																
Safety valves (PWR)	2						VI					VI																
Safety valves (BWR)	2						VI			VI																		
Air-operated solenoid valves	1							VI																				
Electrically-operated solenoid valves	1							VI																				
Reactor coolant pump seals	1							I																				
Main steam isolation valves	1							VI																				
Motor-operated flow control valves	1								VI																			
Atmospheric dump valves	2											VI																
AFW pumps/drives (elec, diesel, turb)	1										VI																	
Containment spray pumps/drives	1												VI															
Reactor containment fans/drives	1													VI														
Louvers	2													I														
Dampers	2													LI	I													
Supply fans/drives	1														I	I												

COMPONENT \ SYSTEM	Seismic Capacity Level	Control Rod Insertion	Accident Boration	CVCS (Letdown)	CVCS (Seal Injection)	Safety Injection System	RCS Pressure Relief	RCS	Residual Heat Removal System	Main Steam System	Auxiliary Feedwater System	RCS/MS Pressure Relief	Containment Spray System	Reactor Containment Fan Coolers	HVAC Systems	Purge System	Containment Isolation System	Isolation Valve Seal Water System	Penetration Pressurization System	Component Cooling Water System	Service Water System	On-Site AC Power System	On-Site DC Power System	Instrumentation and Controls	Chilled Water System	Diesel Oil Systems	Peripherals	Fire Protection System
Exhaust fans/drives	1														VI	VI												
Cubicle coolers															I													
Air handling units	3														LI													
Filters	2														I	I												
Component cooling water pumps/drives	1																			VI								
Service water system pumps/drives	1																				VI							
Strainers	2																				I							
Butterfly valves	1														I	VI	VI				VI							
Air-operated valves	1																VI											
Air-operated pressure control valves	1																	VI										
Diesel generators	1																					VI						
Diesel oil system (piping/pumps/valves)	1																					VI						
Air starting systems (accumulator)	1																					VI						
Lube oil systems	1																					VI					VI	
Combustion air intake louvers	1																					VI						
ESF sequencers	3																					VI		VI				
Motor control center internals	2-3																					VI	VI	VI				

SYSTEM COMPONENT	Seismic Capacity Level	Control Rod Insertion	Accident Boration	CVCS (Letdown)	CVCS (Seal Injection)	Safety Injection System	RCS Pressure Relief	RCS	Residual Heat Removal System	Main Steam System	Auxiliary Feedwater System	RCS/MS Pressure Relief	Containment Spray System	Reactor Containment Fan Coolers	HVAC Systems	Purge System	Containment Isolation System	Isolation Valve Seal Water System	Penetration Pressurization System	Component Cooling Water System	Service Water System	On-Site AC Power System	On-Site DC Power System	Instrumentation and Controls	Chilled Water System	Diesel Oil Systems	Peripherals	Fire Protection System
Switchgear internals	3																					VI		VI				
Isolation amplifiers	1																					VI						
Connections/mounting	3																					VI						
Transformers	1																					VI						
Batteries (including mounting)	2																						VI					
Battery racks	2																						VI					
Battery chargers	2																						VI					
Inverters (AC to DC)	1																						VI					
DC distribution switchboard internals	3																						VI	VI				
Radiation monitoring equipment	2																							I				
ESF/RPS actuation cabinet internals	2																							VI				
Local instrument racks	2																							VI				
Control panels/boards internals	2																							VI				
Local instrument racks	3																							VI				
Limit switches	2																							VI				
Electrical distribution equipment	3																							VI				
Ion chamber electrical connections	3																							VI				

SYSTEM COMPONENT	Seismic Capacity Level	Control Rod Insertion	Accident Boration	CVCS (Letdown)	CVCS (Seal Injection)	Safety Injection System	RCS Pressure Relief	ADS	Residual Heat Removal System	Main Steam System	Auxiliary Feedwater System	RCS/MS Pressure Relief	Containment Spray System	Reactor Containment Fan Coolers	HVAC Systems	Purge System	Containment Isolation System	Isolation Valve Seal Water System	Penetration Pressurization System	Component Cooling Water System	Service Water System	On-Site AC Power System	On-Site DC Power System	Instrumentation and Controls	Chilled Water System	Diesel Oil Systems	Peripherals	Fire Protection System
ΔP/P transmitters	3																							VI				
ΔP/P switches	3																							VI				
Temperature switches	3																							VI				
Flow switches	3																							VI				
Relays	3																							VI				
Process control equipment	3																							VI				
Interlocks (mechanical/electrical)	3																							VI				
Bistables	3																							VI				
Indicators/power supplies	3																							VI				
Chillers	2																								I			
Chiller pumps/drives	1																								VI			
Fire detection devices	2-3																											VI
Fire deluge (Halon, CO2, water)	1-2																											VI
Bearing cooling system	2																										VI	
Air compressors	2																							VI				

134

APPENDIX B

Master List of Safety-Related Equipment

Millstone Unit 3

BEST COPY AVAILABLE

System / Component*	Abbreviation*	Page*
Auxiliary steam		
1. temperature element, primary	TE	2
2. temperature switch	TS	3
Blowdown, steam generator		
3. valve, containment, trip	CTV	4
4. valve, solenoid	SOV	5
Battery, 125v station		
5. battery	BAT	6
6. charger, battery	CHGR	7
7. panel	PNL	8
8. tank	TK	11
Component cooling (charging)		
9. pump	P	11
10. valve, air operated	AOV	11
11. valve, solenoid	SOV	12
12. valve, temperature	TV	13
13. valve, relief	RV	13
14. switch, temperature	TS	14
15. relay, computing, selecting, or booster, temperature	TY	14
16. switch, pressure	PS	15
17. temperature element, primary	TE	15
Component cooling (safety injection)		
18. tank	TK	15
19. pump	P	16
20. valve, relief	RV	16
Component cooling (primary or reactor)		
21. tank	TK	17
22. valve, motor operated	MOV	17
23. valve, air operated	AOV	19
24. valve, flow	FV	21
25. valve, level	LV	22
26. valve, solenoid	SOV	22
27. valve, temperature	TV	25
28. valve, relief	RV	25

* nomenclature and reference pages from Millstone qualification summary

System / Component	Abbreviation	Page
Component cooling (primary or reactor) - cont.		
29. switch, transfer	TRS	28
30. indicator, flow	FI	28
31. pump	P	28
32. switch, flow	FS	29
33. relay, computing, selecting, or booster	FY	30
34. exchanger, heat	E	31
35. switch, level	LS	31
36. transmitter, flow	FT	32
Chilled water		
37. valve, containment, trip	CTV	33
38. valve, solenoid	SOV	34
Common electrical		
39. reserved	AAA	35
40. main control board	MCB	35
41. panel	PNL	36
42. temperature bistables	TB	37
43. panel	PNL	38
44. panel, instrument	IPNL	39
45. panel (instrument)	PNL	41
46. panel	PNL	42
Chemical and volume control		
47. tank	TK	46
48. valve, control, level, self actuated	LCV	46
49. valve, motor operated	MV	47
50. valve, air operated	AOV	47
51. valve, analyzer; valve, air operated (Westinghouse)	AV	48
52. valve, containment isolation (Westinghouse)	CV	51
53. valve, control, flow, self actuated	FCV	52
54. valve, flow	FV	53
55. valve, control, hand	HCV	53
56. valve, control, level, self actuated	LCV	53
57. valve, control, pressure, self actuated	PCV	54
58. valve, solenoid	SOV	54
59. valve, solenoid (Westinghouse)	SV	54
60. valve, control, temperature, self actuated	TCV	56
61. valve, relief	RV	57
62. switch, transfer	TRS	58

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System / Component	Abbreviation	Page
Chemical and volume control - cont.		
63. switch, temperature	TS	58
64. relay, computing, selecting or booster, temperature	TY	58
65. analyzer element	AE	59
66. valve, solenoid	SOV	59
67. valve, motor operated	MV	59
68. transmitter, level	LT	61
69. temperature element, primary	TE	61
Containment atmosphere monitoring		
70. valve, containment, trip	CTV	62
71. valve, solenoid	SOV	62
72. pump	P	63
73. radioactivity element, primary	RE	63
74. radiation indicating relay	RIY	63
75. valve, motor operated	MOV	63
Containment vacuum		
76. valve, air operated	AOV	64
77. valve, containment, trip	CTV	64
78. valve, solenoid	SOV	64
79. valve, motor operated	MOV	65
Drains (aerated), reactor plant		
80. valve, containment, trip	CTV	65
81. valve, solenoid	SOV	66
82. switch, level	LS	66
Drains (hydrogenated), reactor plant		
83. valve, containment, trip	CTV	67
81. valve, solenoid	SOV	68
Drains, turbine plant miscellaneous		
82. valve, air operated	AOV	68
83. valve, solenoid	SOV	70
Generator, standby (diesel starting air compressor)		
*** no qualification data provided ***		

System / Component	Abbreviation	Page
Generator, standby (combustion air damper control)		
*** no qualification data provided ***		
Generator, standby (fuel system)		
84. tank	TK	79
85. pump	P	80
86. switch, transfer	TRS	81
87. level indicating switch	LIS	81
Generator, standby (lube oil system)		
*** no qualification data provided ***		
Generator, standby		
*** no qualification data provided ***		
Motor control center, standby		
88. motor control center	MCC	96
Unit substation, standby		
89. unit substation	US	98
90. transformer	X	99
Switchgear, standby (4160V)		
91. circuit breaker, air	ACB	100
92. bus duct	BD	101
93. resistor	RES	101
94. switchgear	SWG	102
95. temperature bistables	TB	102
Fire protection, water		
96. valve, containment, trip	CTV	102
97. valve, solenoid	SOV	103
Feedwater, auxiliary		
98. tank	TK	103
99. pump	P	103

System / Component	Abbreviation	Page

Feedwater, auxiliary - cont.

100. turbine	T	104
101. valve, motor operated	MOV	104
102. valve, air operated	AOV	105
103. valve, solenoid	SOV	105
104. valve, relief	RV	106
105. indicator, flow	FI	106
106. relay, computing, selecting or booster	FY	107
107. controller, indicating, hand	HIC	110
108. switch, hand	HS	114
109. manually initiated converter	HY	121
110. recorder, level	LR	131
111. switch, level	LS	131
112. relay, level, computing, selecting or booster	LY	132
113. switch, pressure	PS	132
114. valve, air operated	AOV	133
115. valve, hand	HV	133
116. manually initiated converter	HY	135
117. transmitter, flow	FT	137
118. transmitter, level	LT	138

Feedwater, pump & driver oil systems

119. exchanger, heat	E	138
120. filter	FLT	139
121. pump	P	139
122. switch, pressure	PS	139
123. valve, relief	RV	140
124. valve, solenoid	SOV	140

Feedwater

125. valve, motor operated	MOV	141
126. valve, level	LV	141
127. valve, solenoid	SOV	142
128. indicator, level	LI	143
129. relay, level, computing, selecting or booster	LY	143
130. valve, containment, trip	CTV	144
131. valve, solenoid	SOV	145
132. transmitter, flow	FT	147
133. transmitter, level	LT	148

Gas, nitrogen

134. valve, containment, trip	CTV	149

System / Component	Abbreviation	Page
Gas, nitrogen - cont.		
135. valve, solenoid	SOV	149
136. valve, solenoid (Westinghouse)	SV	150
Hydrogen recombiner		
137. damper, air operated	AOD	150
138. valve, solenoid	SOV	150
139. compressor	C	150
140. condenser (mechanical)	CND	151
141. exchanger, heat	E	151
142. flow element	FE	151
143. indicator flow	FI	152
144. switch, flow	FS	152
145. transmitter, flow	FT	153
146. indicator, pressure	PI	153
147. panel	PNL	154
148. transmitter, pressure	PT	154
149. recombiner	RBNR	155
150. power receptacle	RCPT	155
151. temperature element, primary	TE	157
152. switch, indicating, temperature	TIS	159
153. switch, temperature	TS	160
154. recorder, analyzer	AR	162
155. analyzer converter	AY	162
Heat tracing		
156. transformer	X	162
157. transformer auxiliaries	XA	163
Air conditioning, control bldg or area		
158. filter	FLT	164
159. panel	PNL	164
160. fan	FN	165
161. valve, control, pressure, self actuated	PCV	167
162. valve, air operated	AOV	167
163. valve, solenoid	SOV	168
164. controller, temperature	TC	169
165. controller, indicating, temperature	TIC	170
166. switch, temperature	TS	171
167. relay, computing, selecting or booster, temperature	TY	171
168. damper	DMP	174

System / Component	Abbreviation	Page
Air conditioning, control bldg or area - cont.		
169. damper, fire	DMPF	174
170. filter	FLT	180
171. damper	DMP	181
172. damper, air operated	AOD	194
173. damper, motor operated	MOD	195
174. valve, solenoid	SOV	196
175. reserved	AAA	196
176. radioactive element, primary	RE	196
177. radiation indicating relay	RIY	197
178. switch, pressure	PS	197
179. air conditioning unit	ACU	197
180. valve, solenoid	SOV	198
181. damper	DMP	199
182. damper, tornado protection	DMPT	199
183. temperature element, primary	TE	202
184. switch, flow	FS	203
185. switch, temperature	TS	204
Glycol heating		
186. switch, pressure	PS	204
Hot water heating		
187. valve, air operated	AOV	205
188. switch, pressure	PS	205
Chilled water, control bldg or area		
189. tank	TK	206
190. pump	P	206
191. chiller	CHL	207
192. heater	H	207
193. pump	P	207
194. indicator, pressure differential	PDI	208
195. switch, pressure differential	PDS	208
196. indicator, pressure	PI	209
197. switch, pressure	PS	209
198. temperature element, primary	TE	210
199. switch, temperature	TS	211
200. switch, position	ZS	212
201. panel	PNL	212
202. switch, indicating, flow	PDIS	213
203. controller, pressure	PC	213

System / Component	Abbreviation	Page
Chilled water, control bldg or area - cont.		
204. controller, indicating, pressure differential	PDIC	214
205. pressure differential relay	PDY	214
206. switch, temperature	TS	215
207. relay, computing, selecting or booster, temperature	TY	215
208. pressure differential valve	PDV	215
209. pressure differential relay	PDY	216
210. valve, temperature	TV	216
211. relay, computing, selecting or booster, temperature	TY	219
212. transmitter, pressure differential	PDT	221
213. temperature element, primary	TE	221
Ventilation, diesel generator bldg		
214. fan	FN	221
215. controller, temperature	TC	222
216. controller, indicating, temperature	TIC	222
217. relay, computing, selecting or booster, temperature	TY	223
218. damper, motor operated	MOD	224
219. switch, temperature	TS	225
220. damper, tornado protection	DMPT	226
Ventilation, engineered safety features bldg		
221. fan	FN	228
222. air conditioning unit, self contained	ACUS	229
223. controller, temperature	TC	229
224. controller, indicating, temperature	TIC	230
225. switch, temperature	TS	230
226. relay, computing, selecting or booster, temperature	TY	231
227. damper, fire	DMPF	231
228. damper	DMP	234
229. damper, air operated	AOD	240
230. damper, motor operated	MOD	242
231. valve, solenoid	SOV	243
232. damper	DMP	245
233. temperature element, primary	TE	245
234. switch, flow	FS	246
Ventilation, reactor plant		
235. filter	FLT	246

System / Component	Abbreviation	Page
Ventilation, reactor plant - cont.		
236. panel	PNL	247
237. switch, temperature	TS	248
238. fan	FN	249
239. controller, temperature	TC	250
240. controller, indicating, temperature	TIC	250
241. relay, computing, selecting or booster, temperature	TY	251
242. damper, fire	DMPF	253
243. filter	FLT	260
244. damper	DMP	260
245. damper, air operated	AOD	266
246. damper, motor operated	MOD	272
247. valve, solenoid	SOV	275
248. radioactivity element, primary	RE	281
249. radiation indicating relay	RIY	281
250. switch, pressure	PS	282
251. switch, temperature	TS	282
252. air conditioning unit	ACU	283
253. damper	DMP	283
254. temperature element, primary	TE	285
255. flow element	FE	285
256. switch, flow	FS	287
257. transmitter, flow	FT	289
258. switch, temperature	TS	290
259. panel	PNL	290
Ventilation, containment structure		
260. valve, containment, trip	CTV	290
261. valve, solenoid	SOV	291
Ventilation, main steam valve bldg		
262. fan	FN	291
263. damper, air operated	AOD	292
264. damper, motor operated	MOD	292
265. valve, solenoid	SOV	293
266. switch, temperature	TS	293
Ventilation, yard structures		
267. fan	FN	294
268. silencer (inlet or exhaust)	SIL	294
269. damper	DMP	295

AILABLE

System / Component	Abbreviation	Page
Ventilation, yard structures - cont.		
270. damper, air operated	AOD	295
271 valve, solenoid	SOV	295
272. switch, temperature	TS	296
Heating, ventilating, air conditioning condensing water		
273. damper, fire	DMPF	296
274. damper, motor operated	MOD	297
275. radioactivity element, primary	RE	297
276. radiation indicating relay	RIY	298
Instrument air		
277. valve, pressure	PV	298
278. valve, motor operated	MOV	298
Lighting, AC-diesel generator room		
279. transformer lighting	XL	299
Lighting, AC-primary auxiliary bldg		
280. transformer	X	300
281. transformer lighting	XL	300
Lighting, AC-turbine area		
282. transformer	X	301
283. transformer lighting	XL	302
Leakage monitoring		
284. indicator, temperature	TI	302
285. recorder, temperature	TR	303
286. relay, computing, selecting or booster, temperature	TY	303
287. valve, motor operated	MOV	303
288. transmitter, pressure	PT	304
289. temperature element, primary	TE	305
Main steam		
290. valve, motor operated	MOV	305

System / Component	Abbreviation	Page
Main steam - cont.		
291. valve, containment, trip	CTV	306
292. valve, solenoid (Westinghouse)	SV	307
293. valve, relief	RV	311
294. valve, air operated	AOV	314
295. valve, hand	HV	315
296. valve, solenoid	SOV	316
297. valve, pressure	PV	317
298. valve, solenoid	SOV	318
299. relay, computing, selecting or booster, pressure	PY	319
300. radioactivity element, primary	RE	320
301. radiation indicating relay	RIY	321
302. valve, motor operated	MOV	322
303. transmitter, pressure	PT	322
Neutron monitoring		
304. amplifier	AMPL	324
305. valve, containment isolation (Westinghouse)	CV	325
306. valve, solenoid (Westinghouse)	SV	325
Quench spray, containment		
307. tank	TK	326
308. pump	P	326
309. valve, motor operated	MOV	326
310. valve, air operated	AOV	327
311. valve, solenoid	SOV	327
312. indicator, level	LI	328
313. switch, level	LS	328
314. transmitter, level	LT	330
Reactor coolant, primary loop		
315. transmitter, pressure	PT	331
316. valve, motor operated	MV	331
317. valve, analyzer; valve, air operated (Wh)	AV	331
318. valve, control, level, self actuated	LCV	332
319. valve, solenoid	SOV	332
320. valve, solenoid (Westinghouse)	SV	332
321. indicator, pressure	PI	333
322. panel	PNL	333
323. relay, level, computing, selecting or booster	LY	334

System / Component	Abbreviation	Page
Reactor coolant (primary loop) - cont.		
324. relay, computing, selecting or booster, pressure	LY	334
325. relay, computing, selecting or booster, temperature	TY	335
326. transmitter, flow	FT	336
327. transmitter, level	LT	338
328. transmitter, pressure	PT	338
329. temperature element, primary	TE	339
Residual heat removal		
330. valve, control, flow, self actuated	FCV	339
331. valve, control, hand	HCV	340
332. valve, relief	RV	340
333. valve, motor operated	MV	341
334. transmitter, flow	FT	341
335. valve, motor operated	MV	342
Radiation monitoring		
336. rack, storage stand	RAK	342
337. radioactivity element, primary	RE	343
338. radiation indicating relay	RIY	346
Reactor protection		
339. box, junction	JB	349
340. rack, storage stand	RAK	349
341. box, junction	JB	350
Containment recirculation spray		
342. exchanger, heat	E	350
343. pump	P	351
344. valve, motor operated	MOV	351
345. indicator, level	LI	353
346. indicator, pressure	PI	353
347. switch, indicating, flow	FIS	354
348. recorder, level	LR	354
349. relay, level, computing, selecting or booster	LY	354
350. relay, level, computing, selecting or booster, pressure	PY	355

System / Component	Abbreviation	Page
Containment recirculation spray - cont.		
351. transmitter, pressure	PT	355
352. valve, motor operated	MOV	356
Station containment bus (vital), AC supply including transformer & transformer switch		
353. panel	PNL	357
354. transformer	X	359
355. transformer distribution	XD	360
Spent fuel pool cleaning & cleanup (including pool and auxiliary)		
356. exchanger, heat	H	361
357. pump	P	362
358. valve, relief	RV	362
359. indicator, temperature	TI	362
360. relay, computing, selecting or booster, temperature	TY	363
361. switch, level	LS	363
362. temperature element, primary	TE	364
Steam generator, chemical feed		
363. valve, air operated	AOV	364
364. valve, solenoid	SOV	365
Safety injection, high pressure		
365. valve, motor operated	MV	365
366. valve, analyzer; valve, air operated (WH)	AV	367
367. valve, containment isolation (Westinghouse)	CV	368
368. valve, solenoid (Westinghouse)	SV	369
369. valve, relief	RV	370
370. valve, motor operated	MV	370
Safety injection, low pressure		
371. valve, motor operated	MV	371
372. valve, analyzer; valve, air operated (WH)	AV	371
373. valve, containment isolation (Westinghouse)	CV	374
374. valve, solenoid (Westinghouse)	SV	375
375. valve, relief	RV	375
376. valve, motor operated	MV	376

System / Component	Abbreviation	Page
Sampling, post-accident		
377. panel	PNL	378
378. reserved	AAA	378
379. valve, containment, trip	CTV	378
380. valve, solenoid	SOV	379
Sampling, reactor plant		
381. valve, containment, trip	CTV	380
382. valve, containment, isolation (Westinghouse)	CV	382
383. valve, solenoid	SOV	382
384. valve, solenoid (Westinghouse)	SV	386
Steam vents, safety valves		
385. valve, excess flow	EFV	386
Service water (nuclear)		
386. pump	P	389
387. valve, pressure	PV	390
388. valve, motor operated	MOV	391
389. valve, air operated	AOV	393
390. valve, pressure	PV	394
391. valve, solenoid	SOV	394
392. valve, temperature	TV	395
393. valve, relief	RV	395
394. indicator, pressure	PI	398
395. switch, indicating, flow	FIS	398
396. switch, indicating, pressure differential	PDIS	399
397. controller, temperature	TC	399
398. controller, indicating, temperature	TIC	400
399. relay, computing, selecting or booster, temperature	TY	400
400. valve, motor operated	MOV	401
401. radioactivity element, primary	RE	402
402. radiation indicating relay	RIY	402
403. switch, pressure	PS	403
404. transmitter, flow	FT	404
405. temperature element, primary	TE	404
Vital bus, AC supply (to bus)		
406. transformer distribution	XD	405
407. inverter	INV	405

AVAILABLE

System / Component	Abbreviation	Page
Vital bus, AC supply (to bus) - cont.		
408. switch	SW	406
409. panel	PNL	406
Vents, gaseous reactor plant		
410. valve, containment, trip	CTV	407
411. valve, solenoid	SOV	407
Water treating, chlorination		
412. valve, air operated	AOV	408
413. valve, solenoid	SOV	409
Reserved		
414. reactor penetrations	RCP	410
Chemical & volume control		
415. blender	BL	422
416. demineralizer	DEMN	422
417. exchanger, heat	E	423
418. filter	FLT	424
419. connection, flow	FP	425
420. transmitter, flow	FT	426
421. controller, hand	HC	426
422. valve, control, hand	HCV	426
423. indicator, level	LI	427
424. valve, motor operated	MV	428
425. pump	P	430
426. orifice, restriction	RO	432
427. valve, relief	RV	432
428. temperature digital computer (Westinghouse)	TD/	432
429. tank	TK	433
430. indicator, position	ZI	433
431. transmitter, position	ZT	434
Reactor core temperature		
432. temperature element, primary	TE	434
Feedwater		
433. valve, control, flow, self actuated	FCV	442

ABLE

15.2

System / Component	Abbreviation	Page
Feedwater - cont.		
434. indicator, level	LI	442
435. transmitter, level	LT	445
Main steam		
436. flow element	FE	448
437. indicator, pressure	PI	448
438. switch, position	ZS	451
Quench spray, (containment)		
439. indicator, level	LI	452
440. recorder, level	LR	453
Reactor coolant (primary loop)		
441. reserved	AAA	453
442. valve, analyzer; valve, air operated (WH)	AV	453
443. switch, indicating, flow	FIS	455
444. controller, hand	HC	456
445. valve, control, hand	HCV	456
446. indicator, level	LI	457
447. transmitter, level	LT	457
448. valve, motor operated	MV	458
449. pump	P	459
450. valve, control, pressure, self actuated	PCV	460
451. indicator, pressure	PI	461
452. transmitter, pressure	PT	461
453. rack, storage stand	RAK	462
454. reactor vessel	REV	462
455. steam generator	SG	462
456. support, equipment	SUP	463
457. valve, solenoid (Westinghouse)	SV	463
458. temperature element, primary	TE	464
459. indicator, temperature	TI	467
460. tank	TK	468
461. indicator, position	ZI	468
462. transmitter, position	ZT	468
Residual heat removal		
463. exchanger, heat	E	469
464. switch, indicating, flow	FIS	469
465. pump	P	470

System / Component	Abbreviation	Page
Reactor protection		
466. box, junction	JB	470
467. rack, storage stand	RAK	471
468. switchgear	SWG	473
Safety injection, high pressure		
469. rack, storage stand	RAK	474
470. exchanger, heat	E	474
471. transmitter	FT	474
472. pump	P	475
Safety injection, low pressure		
473. valve, control, hand	HCV	475
474. valve, solenoid (Westinghouse)	SV	475
475. tank	TK	477
476. transmitter, position	ZT	477

APPENDIX C

Comparison of Subjective Seismic Capacity Levels with Levels Inferred by Qualification Data

Table C-1. Reactivity control components.

System / Components	Ranking[1]	Qualification[2] Level (ZPA) h	v	Inferred[3] Seismic Capacity	Source[4]
Control Rod Insertion					
a. Reactor trip breakers	VI-2	n/a	n/a		
b. Rod bottom indication	LI-3	n/a	n/a		
c. CRD system (BWR)	VI-1	n/a	n/a		
Accident Boration					
d. Charging pumps and drives	VI-1	.27	.16	3	MU3(11)
		2.1g		OK	MU3(430)
e. Motor operated valves	VI-1	3g			MU3(17)
f. Check valves	VI-1	n/a	n/a		
g. Explosive valves (BWR)	VI-1	n/a	n/a		
h. Pressure relief valves	I-2	3g		1	MU3(57)

NOTES:

1. Subjective importance group (VI, I, or LI) and seismic capacity level (1, 2 or 3) as determined by the Component Identification Working Group.

2. Qualification ZPA in horizontal (h) and vertical (v) directions as given in the indicated source; "n/a" appears when no qualification data was available in either source.

3. Seismic capacity level inferred by qualification data. For a seismic capacity different from the working group estimate, the "new" value is listed; otherwise "OK" is given. Note, however, that the subjective capacity level was not readjusted, either upwards or downwards, to conform with the inferred value.

4. MU3( ) - Millstone Unit 3 (reference page)
HG( ) - Hosgri (summary reference number)

Table C-2. Reactor coolant inventory control components.

System / Components	Ranking[1]	Qualification[2] Level (ZPA)		Inferred[3] Seismic Capacity	Source[4]
		h	v		
Chemical and Volume Control (Letdown)					
a. Isolation Valves	VI-1	3g		OK	MU3(51)
Chemical and Volume Control (Charging, Seal Injection)					
b. Seal injection filters	I-2	1.5	1.0	OK	MU3(424)
c. Air operated flow control valves	VI-1	3g		OK	MU3(11)
d. Charging pumps	VI-1	.27	.16	3	MU3(11)
Safety Injection System					
e. Safety injection pumps and drives	VI-1	.23 2.1g	.12	3 1	MU3(16) MU3(475)
f. Motor operated valves	VI-1	3g		OK	MU3(365)
g. Check Valves	VI-1	n/a	n/a		
h. Relief valves	I-2	3g		1	MU3(365)
i. Residual heat removal pumps and drives	VI-1	2.1g		OK	MU3(470)
j. Core spray pumps and drives	VI-1	n/a	n/a		
Reactor Coolant System(s) Pressure Relief					
k. Power operated relief valves	I-2	n/a	n/a		
l. Motor operated valves	I-1	3g		OK	MU3(331)
m. Safety valves (PWR)	VI-2	n/a	n/a		
n. Safety valves (BWR)	VI-1	n/a	n/a		

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Table C-3. Reactor coolant system pressure boundary components.

System / Components	Ranking[1]	Qualification[2] Level (ZPA) h	v	Inferred[3] Seismic Capacity	Source[4]
Reactor Coolant System					
a. Air/electrically operated solenoid valves	VI-1	3g		OK	MU3(332)
b. Reactor coolant pump seals	I-2	n/a	n/a		
c. Main steam isolation valve (BWR)	VI-1	3g		OK	MU3(306)
d. Swing check valves in peripheral piping	VI-1	n/a	n/a		
Reactor Coolant System Pressure Relief					
(See Table C-2. Reactor coolant inventory control components.)					

AILABLE

Table C-4. Core cooling control components.

System / Components	Ranking[1]	Qualification[2] Level (ZPA) h	v	Inferred[3] Seismic Capacity	Source[4]
Safety Injection System					
(See Table C-2. Reactor coolant inventory control components.)					
Residual Heat Removal System					
a. Pumps and drives	VI-1	2.1g		OK	MU3(470)
b. Motor operated valves	VI-1	3g		OK	MU3(331)
c. Motor operated flow control valves	VI-1	3g		OK	MU3(52)
d. Air operated flow control valves	VI-1	2.1g		OK	MU3(453)
e. Swing check valves	VI-1	n/a	n/a		
f. Isolation condenser valves	VI-1	n/a	n/a		
Main Steam					
g. SRVs (safety relief valves)	VI-1		3g	OK	MU3(16)

Table C-5. Decay heat removal components.

System / Components	Ranking[1]	Qualification[2] Level (ZPA) h	v	Inferred[3] Seismic Capacity	Source[4]
Auxiliary Feedwater System					
a. Pumps and drives (etc., diesel, turbine)	VI-1	.32	.13	3	MU3(103)
b. Motor operated valves	VI-1	3g		OK	MU3(104)
c. Air operated flow control valves	VI-1	3g		OK	MU3(105)
d. Swing check valves	VI-1	n/a	n/a		
Reactor Coolant System					
(See Table C-3. Reactor coolant system pressure boundary components.)					
Residual Heat Removal System					
(See Table C-4. Core cooling system components.)					

Table C-6. Plant environment components.

System / Components	Ranking[1]	Qualification[2] Level (ZPA) h	v	Inferred[3] Seismic Capacity	Source[4]
Containment Spray System					
a. Pumps and drives	VI-1	.25	.15	3	MU3(351)
Reactor Containment Fan Coolers					
b. Fan and drivers	VI-1	n/a	n/a		
c. Louvers	I-2	n/a	n/a		
d. Backdraft dampers	LI-1	.5	.15	3	MU3(181)
Purge System					
e. Supply fans	I-1	.5	.15	3	MU3(165)
f. Exhaust fans	VI-1	.3	.15	3	MU3(165)
g. Butterfly valves	VI-1	3g		OK	MU3(392)
h. Filters	I-2	.5	.15	3	MU3(164)
HVAC System					
i. Supply fans and drives	I-1	.5	.15	3	MU3(165)
j. Exhaust fans and drives	VI-1	.3	.15	3	MU3(165)
k. Cubical coolers	I	n/a	n/a		
l. Air handling units	LI-3	.32	.13	OK	MU3(229)
m. Filters	I-2	.5	.15	3	MU3(139)

161

Table C-7. Containment integrity components.

System / Components	Ranking[1]	Qualification[2] Level (ZPA) h	v	Inferred[3] Seismic Capacity	Source[4]
Containment Isolation System					
a. Motor operated valves	VI-1	3g		OK	MU3(63)
b. Air operated valves	VI-1	3g		OK	MU3(64)
c. Butterfly valves	VI-1	3g		OK	MU3(392)
Containment Spray System					
(See Table C-6. Plant environment components.)					
Reactor Containment Fan System					
(See Table C-6. Plant environment components.)					
Isolation Valve Seal Water System					
d. Swing check valves	VI-1	n/a	n/a		
e. Air operated pressure control valves	VI-1	3g		OK	MU3(167)
Penetration Pressurization System					

Table C-8. On-site electric power components.

System / Components	Ranking[1]	Qualification[2] Level (ZPA) h	v	Inferred[3]3 Seismic Capacity	Source[4]
On-Site AC Power					
a. Diesel generator	VI-1	.85	.85	3	HG(6)
b. Diesel oil system (piping, pumps, valves)	VI-1	n/a	n/a		
c. Air starting systems (accumulator)	VI-1	n/a	n/a		
d. Lube oil systems	VI-1	n/a	n/a		
e. Combustion air intake louvers	VI-1	n/a	n/a		
f. ESF sequences	VI-1	n/a	n/a		
g. Motor control center internals	VI-2/3	.32	.15	3	MU3(96)
h. Switchgear internals	VI-3	.25	.15	OK	MU3(103)
i. Isolation amplifiers	VI-1	n/a	n/a		
j. Connections/mounting	VI-3	n/a	n/a		
k. Transformers	VI-1	.25	.15	3	MU3(299)
On-Site DC Power					
l. Batteries (including mounting)	VI-2	2.5 .25	1.1 .15	1 3	HG(4) MU3(6)
m. Battery racks	VI-2	3.0	.65	1	HG(4)
n. Battery chargers	VI-2	2.2 .25	1.3 .15	1 3	HG(3) MU3(7)
o. Inverters (DC to AC)	VI-1	1.5	1.0	2	HG(10)
p. DC distribution switchboard internals	VI-3	n/a	n/a		

Table C-9. Instrumentation and control components.

System / Components	Ranking[1]	Qualification[2] Level (ZPA)		Inferred[3] Seismic Capacity	Source[4]
		h	v		
a. Radiation monitoring equipment	I-2	.5	.2	3	MU3(343)
b. ESF/RPS actuation cabinet internals	VI-2	n/a	n/a		
c. Local instrument racks	VI-2	n/a	n/a		
d. Control panels/boards internals	VI-2	n/a	n/a		
e. Nuclear instrumentation system (ex-core)	VI-3	2.0	1.33	1	HG(16)
f. Limit switches	VI-2	n/a	n/a		
g. Electrical distribution equipment	VI-3	n/a	n/a		
h. Ion chamber electrical connections	VI-3	n/a	n/a		
i. P/P transmitters (NSSS)	VI-3	2.0	1.33	1	HG(17)
(BOP)		18	18	1	HG(18)
j. P/P switches	VI-3	n/a	n/a		
k. Temperature switches	VI-3	.32	.18	OK	MU3(14)
l. Flow switches	VI-3	.40	.15	OK	MU3(29)
m. Relays	VI-3	.40	.15	OK	MU3(14)
n. Process control equipment	VI-3	n/a	n/a		
o. Interlocks (mechanical/ electrical)	VI-3	n/a	n/a		
p. Bistables	VI-3	.25	.15	OK	MU3(102)
q. Indicators/power supplies	VI-3	n/a	n/a		
r. ESF sequencers	VI-3	n/a	n/a		
s. Motor control center internals	VI-2/3	.25	.13	3	MU3(96)
t. Switchgear internals	VI-3	.25	.15	OK	MU3(102)
u. DC distribution switchgear internals	VI-3	n/a	n/a		
v. Air compressors	VI-2	n/a	n/a		

Table C-10. Components for maintainance of vital auxiliaries.

System / Components	Ranking[1]	Qualification[2] Level (ZPA)		Inferred[3] Seismic Capacity	Source[4]
		h	v		
Closed/Component Cooling Water System					
a. Pumps and drives	VI-1	.27	.16	3	MU3(28)
Service Water System					
b. Pumps and drives	VI-1	.5	.15	3	MU3(389)
c. Motor operated valves	VI-1	3g		OK	MU3(391)
d. Strainers	I-2	n/a	n/a		
e. Butterfly valves	VI-1	3g		OK	MU3(392)
Chilled Water System					
f. Pumps and drives	VI-1	.5	.15	3	MU3(206)
g. ESF sequencers	VI-3	n/a	n/a		
h. Motor control center internals	VI-2/3	.32	.13	3	MU3(96)
i. Switchgear internals	VI-3	.25	.15	OK	MU3(102)
j. Chillers	I-2	.5	.15	3	MU3(107)
Fire Protection System					
k. Fire detection devices	VI-2/3	n/a	n/a		
l. Fire deluge (Halon, CO2, water)	VI-1/2	n/a	n/a		
Peripherals					
m. Bearing cooling system	VI-2	n/a	n/a		
n. Lube oil system	VI-1	n/a	n/a		

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Current probabilistic risk assessment (PRA) methods for nuclear power plants utilize seismic "fragilities"-- probabilities of failure conditioned on the severity of seismic input motion -- that are based largely on limited test data and on engineering judgement. Under the NRC Component Fragility Research Program (CFRP), the Lawrence Livermore National Laboratory (LLNL) has developed and demonstrated procedures for using test data to derive probabilistic fragility descriptions for mechanical and electrical components. As part of its CFRP activities, LLNL systematically identified and categorized components influencing plant safety in order to identify "candidate" components for future NRC testing. Plant systems relevant to safety were first identified; within each system components were then ranked according to their importance to overall system function and their anticipated seismic capacity. Highest priority for future testing was assigned to those "very important" components having "low" seismic capacity. This report describes the LLNL prioritization effort, which also included application of "high-level" qualification data as an alternate means of developing probabilistic fragility descriptions for PRA applications.

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